Design of a 6-DOF Haptic Master for Tele-operating a Mobile-manipulator

†Dongseok Ryu, †Chang-hyun Cho, †Munsang Kim, †Chongwon Lee, ††Jaebok-Song

†Advanced Robotics Research Center
Korea Institute of Science and Technology
39-1 Hawolgok-dong, Sungbuk-ku, Seoul, Korea. 136-791
sayryu@kist.re.kr

††Mechatronics and Control Laboratory
Department of Mechanical Eng., Korea University
5 Anam-dong, Sungbuk-ku, Seoul, Korea. 136-701
jbsong@korea.ac.kr

Abstract

In this paper, a new design of a 6DOF haptic master is presented. It is compose of two mechanical part. lower mechanism is planar 3DOF, and upper mechanism which can expand DOFs of the haptic master into 6DOF is attached serially on the lower mechanism part. In making both parts, we use a parallel mechanism. This can make it have high stiffness and accuracy. Besides, this can make the actuators fixed on the base and hence exclude inertia of the actuators from motion. In the result, presented haptic master has high back-drivability.

We design it in the consideration of the application tele-operating a mobile-manipulator. Because It can only use 3 actuators in force feedback with the directions of planar 3DOF(x,y tanslation, z rotaion), It depart from the existing 6DOF parallel hatic masters which must be controlled whole six actuators in spite of generating just few DOFs of force.

After introducing the mechanism, working principle is simply analyzed from a kinematic point of view. It can be used efficiently and intuitively in the application that main operation is possible with planar 3DOFs motion and 6DOF motion is needed for a while.

1. Introduction

Haptic device becomes not only a deivce for virtual reality and tele-operation but also a new paradigm as an human computer interface. For last decades, lots of haptic devices have been developed. In the beginning, developing the pointing device which has only cartesian 3DOF(x, y, z translation) was mainly focused. Afterwards, a lot of parallel haptic devices which have 6DOF and good performance have been introduced.

Haptic device is similar with general robots in the point that it should be able to apply force to the end-effector(it comes handle in haptic device) as much as possible. However, it differ from general robots in the fact that it should be back drivable so that an operator can swing the end-effector easily without any resistance, while there is no applying force.

Haptic device should be transparent [1]. this means that it has wide range of z-depth, which implies it has not only convenience of manipulation with low inertia itself but also capability of representing large amount of force at the same time [2].

In designing haptic device with serial mechanism, it is difficult to achieve precision and rigidity, because error is accumulate through the joint from link to other. As matters worse, increasing DOFs of mechanism, we hardly find the way to fix all actuators on the base, and we can not help but place some of the actuator on the moving links. Unfortunately, the inertia caused by the motion of the actuators reduces back drivability, and it means that the performance get down and transparency is gone away. Mentioned shortcomings bring difficulties to get more than 3DOF with serial mechanism, as designing haptic device which is satisfied the required performance. And several ideas have been proposed such as adjusting the inertia of actuator using weight balance or bring the power of link from the base [3,4].

Fig 1. Overview of the haptic master

Recently, various parallel haptic devices with multi DOF are introduced [5-7]. As using parallel mechanism, high stiffness and accuracy can be achieved easily. Moreover, it makes all actuators installed on the base without moving, and hence the performance increases excluding the inertia of actuator.

It is desired that full 6DOF motion is represent, considering limitation of usage of 3DOF device. However, actually it is rare case the application required whole 6DOF for all time during operation. We are still noticed that it can be more general that some specified DOFs is mainly needed in the most of application except several moments asking whole 6DOF. If general 6DOF parallel haptic device would be used in this case, all actuators should be controlled all the time regardless of number of DOFs needed. It leads unwilling complexity and difficulty in control, much more, it means inefficiency of consuming power. Considering it is hard to control to all actuator identically, it can be more practical way to provide essential DOF with kinematic constraints.

In developing haptic device, we have to pay attention to not only DOF and performance but also convenience and fitness concerning about the application. This paper starts from the question, which is proper and efficient in tele-operating mobile manipulator. In developing haptic device, they are inclined to classify DOF as cartesian DOF(x, y, z translation) and rotational DOF(roll, pitch, yaw rotation). And they are likely to make much of the pointing device has translation 3DOF. Since now, expending their device's DOFs into 6, it have shown the tendency that they attach another rotational 3DOF mechanism on their developed pointing device or develop a new device get 6DOF with parallel mechanism.

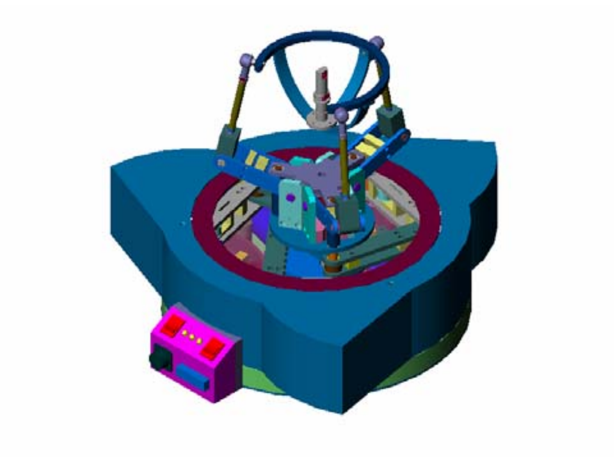

Fig 2. 3D modeling for prototype manufacture

But actually there are lots of applications need planar 3DOF(x, y translation, z rotation), including control of a mobile robot. If the things that the user mainly asks in the application would be operating with planar motions, and if additional asks such as switching into 3D operation mode would still remain, we should be change the approach.

we propose a new design of a 6DOF haptic master, as shown Fig.1 and Fig.2. It depart from the existing designs in that it can use exact three actuators in force feedback on planar motion, beyond the existing 6DOF parallel hatic masters which must be controlled whole six actuators in spite of generating just few DOFs of force. So presented haptic master is utilized efficiently and intuitively in the application as mentioned above.

2. Design concept and architecture

It is compose of two mechanical parts. Lower mechanism is planar 3DOF, and upper mechanism which can expand DOFs of the haptic master into 6DOF is attached serially on the lower part. In making both parts, we adapt a parallel mechanism. This leads to achieving high stiffness and accuracy. Besides, this can make the actuators fixed on the base and hence exclude inertia of the actuators from motion. In the result, presented haptic master has high back-drivability.

Using revolute and prismatic joints as the kinematic pairs, we obtain seven possible limbs arrangements; RRR, RRP, RPR, PRR, RPP, PRP, and PPR. Further, if we limit ourselves to manipulators with three identical limb structures, only seven 3-dof planar parallel manipulators are feasible [8,9]. In robot design, prismatic joint is preferred in order to get high resistance from disturbance on the end-effector. On the contrary, as back drivability is regarded as an positive factor in haptic, that is why we adopt 3RRR planar mechanism among the seven mentioned above. 3RRR mechanism shown as Fig.3.

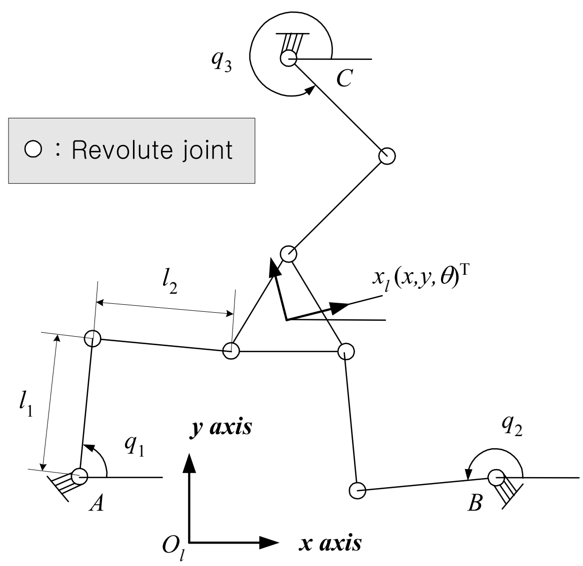

Fig 3. Architecture of the lower mechanism.

There are various spatial parallel devices [10-12]. In the same reason, 3RRS parallel mechanism is applied as the upper mechanism part, as shown Fig.4. Using revolute joint has additional merits, such as stiffness and rigidity which are resulted from making structure simple and firm.

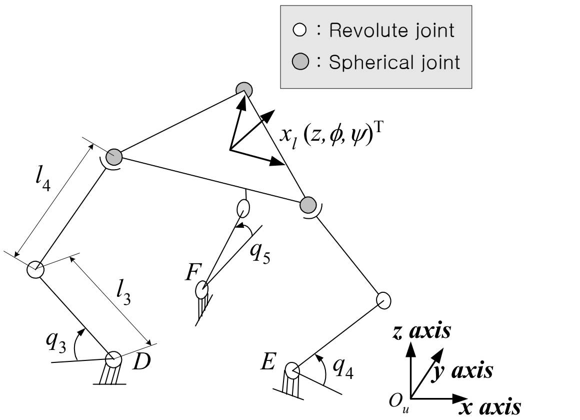

Fig 4. Architecture of the upper mechanism.

Finally, a new 6DOF haptic master is built by assembling both parts together serially, shown Fig.5.

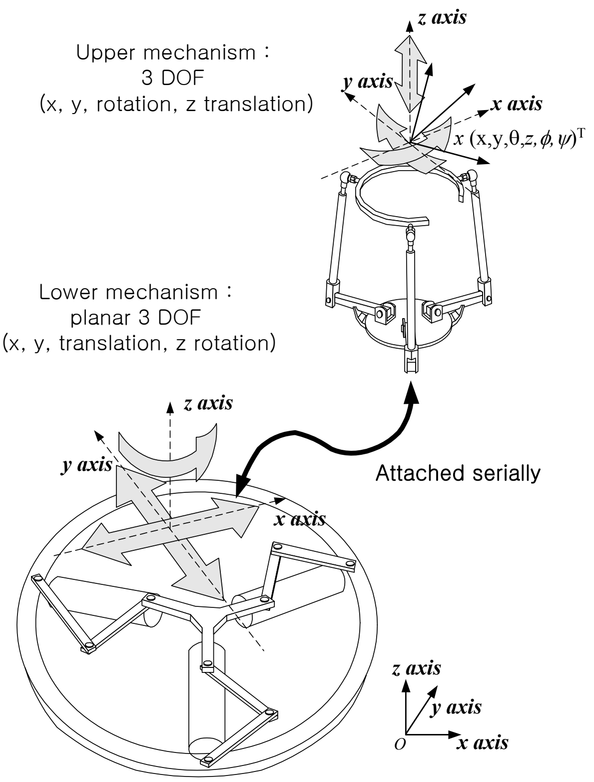

Fig 5. Architecture of the proposed haptic master.

Not both mechanism parts are dependent in the 3D motions, but the 3D motion is divided and transferred to each mechanism according to DOF. Force feed-back to planar DOF is accomplished by controlling exact three actuators of lower mechanism, and this means that complex control problem is solved kinematically.

But if actuators for driving upper mechanism would be placed on the end-effector of lower mechanism, these will move together along the motion of end-effector of lower mechanism part. As a consequence it follows that their inertia reduces back drivability and performance. the solution to avoid this trouble might be transmitting the power from base or mounting light actuator. We chose the former.

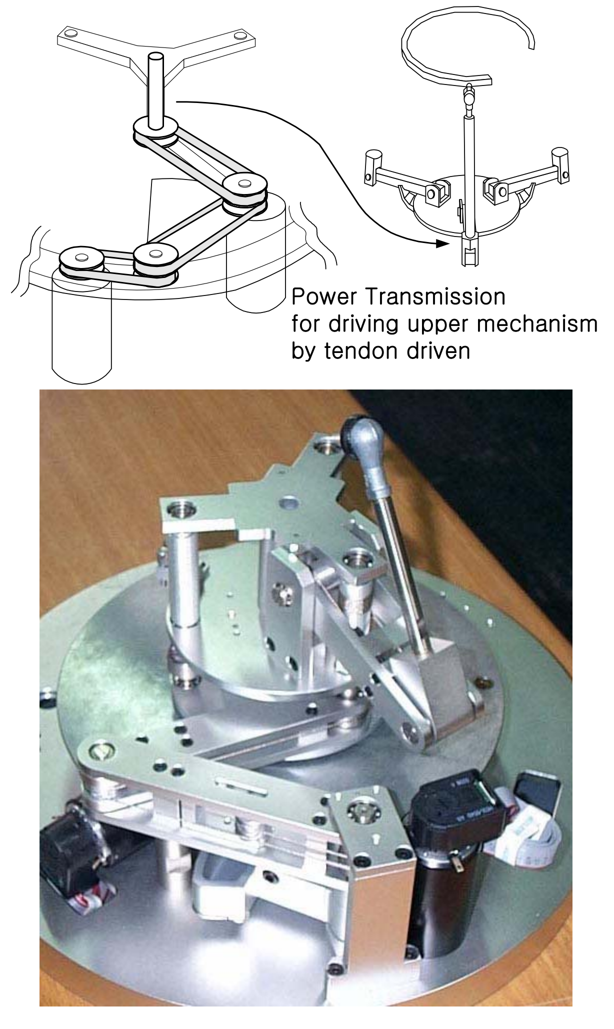

Fig 6. Tendon driven mechanism for power transmitting.

Utilizing links and structure of lower mechanism, the power for driving upper part can be transmitted from actuators fixed on the base. Installing coaxial pulleys on each joint of links of lower part, tendon driven structure was designed as shown Fig.6. Actually, It makes both mechanical parts constrain. In the result, there becomes kinematical dependency and couple together.

3. Working principle from kinematic view

The tendon driven structure described last chapter couple both mechanism parts and hence it bring constraint each other. At first, joint variables and cartesian variables denoted below, refer to Fig. 3, 4, and 5.

$$\begin{aligned} \boldsymbol{x_l} &= (x \quad y \quad \theta)^T \quad \in \boldsymbol{R}^3 \\ \boldsymbol{x_u} &= (z \quad \phi \quad \varphi)^T \quad \in \boldsymbol{R}^3 \\ \boldsymbol{x} &= (x_l \quad x_u)^T \quad \in \boldsymbol{R}^6 \\ \boldsymbol{q_l} &= (q_{l1} \quad q_{l2} \quad q_{l3})^T \quad \in \boldsymbol{R}^3 \\ \boldsymbol{q_u} &= (q_{u1} \quad q_{u2} \quad q_{u3})^T \quad \in \boldsymbol{R}^3 \\ \boldsymbol{q} &= (q_l \quad q_u)^T \quad \in \boldsymbol{R}^6 \end{aligned} \tag{1}$$

When it moves with small deviation, we can represent the relation between joint space and catesian space as an derivative equation. when it is dealt isolately, the relation is described Eq. (2).

$$\begin{aligned} \boldsymbol{J_{ql}} \cdot \mathrm{d}\boldsymbol{q_l} &= \boldsymbol{J_{xl}} \cdot \mathrm{d}\boldsymbol{x_l} \\ \boldsymbol{J_{qu}} \cdot \mathrm{d}\boldsymbol{q_u} &= \boldsymbol{J_{xu}} \cdot \mathrm{d}\boldsymbol{x_u} \end{aligned} \tag{2}$$

In this Eq. (2), $\boldsymbol{J_{ql}} \in \boldsymbol{R}^3$, $\boldsymbol{J_{xl}} \in \boldsymbol{R}^3$ are jacobians of lower parallel mechanism, and $\boldsymbol{J_{qu}} \in \boldsymbol{R}^3$, $\boldsymbol{J_{xu}} \in \boldsymbol{R}^3$ are jacobians of upper parallel mechanism.

However, Both mechanisms are no longer independent with tendon driven structure. There becomes dependency. we denote it totally including constraint, as shown Eq. (3),

$$\boldsymbol{J_q} \cdot \mathrm{d}\boldsymbol{q} = \boldsymbol{J_x} \cdot \mathrm{d}\boldsymbol{x} \tag{3}$$

where,

$$\begin{aligned} \boldsymbol{J_q} &= diag[\mathrm{J_{q1}} \quad \mathrm{J_{q2}} \quad \mathrm{J_{q3}} \quad \mathrm{J_{q4}} \quad \mathrm{J_{q5}} \quad \mathrm{J_{q6}}] \\ \boldsymbol{J_x} &= \begin{bmatrix} \boldsymbol{J_{xl}} & \boldsymbol{J_{xc1}} \\ \boldsymbol{J_{xc2}} & \boldsymbol{J_{xu}} \end{bmatrix} \end{aligned} \tag{4}$$

and $\boldsymbol{J_q}, \boldsymbol{J_x} \in \boldsymbol{R}^6$ are jacobians of proposed haptic master, $\boldsymbol{J_{xc1}}, \boldsymbol{J_{xc2}} \in \boldsymbol{R}^3$ are the terms which mean couple between both mechanism, $\boldsymbol{J_{xl}}, \boldsymbol{J_{xu}} \in \boldsymbol{R}^3$ mean the relation between each parts of joint and cartesian variables along the direction which it can move.

Observing the constraint physically, we can notice that couple term, $\boldsymbol{J_{xc1}}$ are equal to zero matrix and gone away. Moreover, terms in $\boldsymbol{J_{xc2}}$ are equal to zero except the third column. And this means physically that only rotation(z rotation, θ) among the three planar motions(x, y, θ) which can influence upper part by lower mechanism. So we can say that $\boldsymbol{J_x}$ is upper triangular matrix.

we can consider Jacobians described above from a different standpoint. Let $\boldsymbol{T_{joint}}, \boldsymbol{F_{feedback}}, \boldsymbol{J_{eq}}$ are the term which mean the vector of torque of joint space, the vector of feed-back force on the end-effector, the jacobian of haptic master. We can represent the relation of joint torque and force on the cartesian space as shown Eq. (5).

$$\boldsymbol{T_{joint}} = \boldsymbol{J_{eq}} \cdot \boldsymbol{F_{feedback}} \tag{5}$$

Where,

$$\begin{aligned} \boldsymbol{T_{joint}} &= (\boldsymbol{T_{l,q1}} \quad \boldsymbol{T_{l,q2}} \quad \boldsymbol{T_{l,q3}} \quad \boldsymbol{T_{u,q4}} \quad \boldsymbol{T_{u,q5}} \quad \boldsymbol{T_{u,q6}})^T \\ \boldsymbol{F_{feedback}} &= (\boldsymbol{F_x} \quad \boldsymbol{F_y} \quad \boldsymbol{F_\theta} \quad \boldsymbol{F_z} \quad \boldsymbol{F_\varphi} \quad \boldsymbol{F_\psi})^T \\ \boldsymbol{J_{eq}} &= \left(\boldsymbol{J_q}^{-1} \cdot \boldsymbol{J_x}\right)^{T^{-1}} \end{aligned} \tag{6}$$

And pay attention to the order of subscript $\boldsymbol{T_{joint}}, \boldsymbol{F_{feedback}}$ is different with general form. We use this notation for convenience of analysis in the consideration of structural characteristics of mechanism.

We can rewrite $\boldsymbol{J_{eq}}$ below Eq. (7).

$$\boldsymbol{J_{eq}} = \left(\boldsymbol{J_q}^{-1}\right)^{T^{-1}} \cdot \left(\boldsymbol{J_x}\right)^{T^{-1}} \tag{7}$$

It is important weather $\boldsymbol{J_{eq}}$ is singular or not for designing and control the device. Because $\boldsymbol{J_q}$ is diagonal matrix, it is nonsingular and it takes no effect the singularity of $\boldsymbol{J_{eq}}$. so we take notice of only $\boldsymbol{J_x}$, and rewrite the term, $\left(\boldsymbol{J_x}\right)^{T^{-1}}$ in Eq. (7).

$$\boldsymbol{J_x}^T = \begin{bmatrix} \boldsymbol{J_{xl}} & \boldsymbol{J_{xc2}} \\ 0 & \boldsymbol{J_{xu}} \end{bmatrix} \tag{8}$$

Because it is lower triangular matrix, using matrix inversion formulas, we easily get the Eq.(9), and remember that $\boldsymbol{J_{xc2}}$ is singular.

$$\left(\boldsymbol{J_x}^T\right)^{-1} = \begin{bmatrix} \boldsymbol{J_{xl}}^{-1} & \boldsymbol{J_{xl}}^{-1} \cdot \boldsymbol{J_{xc2}} \cdot \boldsymbol{J_{xu}}^{-1} \\ 0 & \boldsymbol{J_{xu}}^{-1} \end{bmatrix} \tag{9}$$

Eq.(9) prove that $\boldsymbol{J_{eq}}$ is nonsingular if and only if $\boldsymbol{J_{xl}}$ and $\boldsymbol{J_{xu}}$ are nonsingular, however $\boldsymbol{J_{xc2}}$ is singular.

It informs us the easy way to calculate the inversion of $\boldsymbol{J_{eq}}$, there is need not to inverse six by six matrix at once but to use the inversion of three by three matrices, $\boldsymbol{J_{xl}}, \boldsymbol{J_{xu}}$.

Practically, it reduces the computational loads of control system.

We can get physical meaning of Eq.(5) with the fact that inverse transpose of $\boldsymbol{J_x}$ still remains lower triangular matrix. It explanations that we can apply force in the direction of planar DOF with not whole six actuators but exact three actuators of lower mechanism.

4. System and application

It is difficult to compare developed haptic master with other devices, cause each device has different structure and configuration. We report the simple specification of our haptic master compared with PHANToM, well-known commercial haptic device, as shown table.1 [3,4].

Table 1. Comparison of presented haptic master and commercial haptic device, PHANToM.

	Presented master	PHANToM
DOF	6	6 / 3 (input 6, feedback 3)
Weight	11Kg (actuator 4Kg)	-
Workspace	110mm diam, 100mm height. cylinder	80 mm length, 170 mm width, 250mm height. cube
Feedback force	continuous 20N, peak 30N force continuous 2Nm, peak 3Nm Torque	continous 1.5N, peak 10N force
Band width	1msec sampling time	250Hz band width

The schematic diagram of tele-operating mobile-manipulator system is shown as Fig. 7. When the operator grips the handle of haptic master and swings it intuitively along the directions that he intend to move, the joint angle is sensed by encoder, and DSP controller calculates the position with gathered data in real time. As DSP controller transmits the position data to operating PC, the PC generate control command for operating mobile manipulator with some algorithm. Finally, local controller in mobile-manipulator receives the command and mobile manipulator move along the motion of operator.

Mobile manipulator will face various situation, exploring environment. It can gather data, such as velocity, distance from detected obstacle, inclination of terrain, internal temperature, error of subsystem, etc. As it report this to the PC, and the operating PC generates force command proper to the situation. Operator is noticed intuitively internal and external situation of mobile manipulator by various effects of forces transferred through the handle.

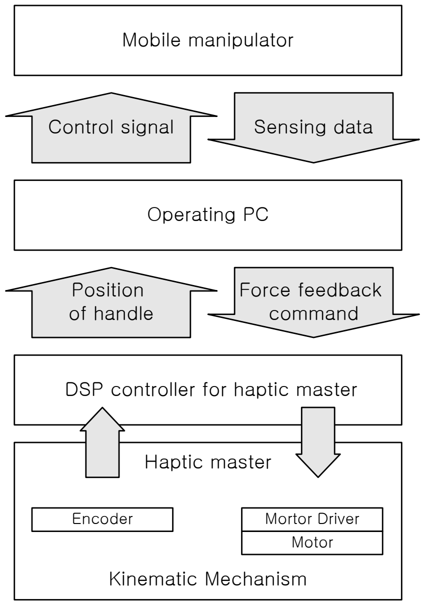

Fig7. Schematic diagram of tele-operating mobile manipulator with haptic master.

In moving mode, using only planar 3DOFs of lower mechanism with kinematic constraint leads the effect that the computational loads for kinematic and dynamic calculation decrease. Consequently, it is easy to control. Moreover it is efficient to save the consuming power. When it switch the mode for manipulating, without mentioning, it can use whole 6DOFs.

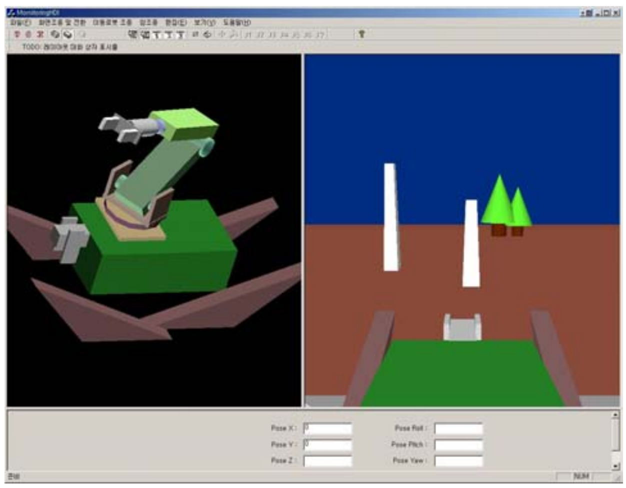

Fig 8. Virtual environment for tele-operation of mobile-manipulator

Before integrating actual system, we make an application that operator can exercise in virtual environment, as shown Fig. 8. the tele-operated mobile manipulator is expensive. In the consideration of control miss, there are some risks that the operator is trained with real system. And it may be damaged by unverified algorithm and force feedback control in haptic master. VR application for tele-operating mobile manipulator is useful as a training method and a developing test-bed.

5. Conclusion

In this work, we present a design of a 6DOF haptic master, which consists of two mechanical parts and tendon driven system. In making both parts, we use an parallel mechanism. This leads to achieving high stiffness and accuracy. Besides, this can make the actuators fixed on the base and hence exclude inertia of the actuators from motion. In the result, presented haptic master has high back-drivability. We design it in the consideration of the application tele-operating a mobile-manipulator. Because it can only use 3 actuators in force feedback with the directions of planar 3DOFs, It depart from the existing 6DOF parallel hatic masters which must be controlled whole six actuators for all time in spite of generating just few DOFs of force. And hence, it can be utilized efficiently and intuitively in the application that main operation requires planar 3DOFs motion and 6DOFs motion is needed for a while. Various experiments are in process with this haptic master.

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