Visually and Haptically Augmented Teleoperation in D&D Tasks Using Virtual Fixtures

Hyosig Kang, Young S. Park, Thomas F. Ewing
Nuclear Engineering Division, Argonne National Laboratory, Argonne, IL 60439, USA
hkang@anl.gov

Eric Faulring, J. Edward Colgate
Department of Mechanical Engineering, Northwestern University, Evanston, IL 60208, USA
colgate@northwestern.edu

Abstract – *This paper describes the enhanced teleoperation in order to improve productivity while reducing risk to human workers from hazardous environment in Decontamination and Decommissioning (D&D) tasks. Due to the difficulty of perceiving the three-dimensional environment with two-dimensional video display, one of the most difficult tasks is to place the tool on the target objects while maintaining proper alignment. To alleviate such difficulty and thus enhance the performance of such three-dimensional tasks, this paper presents the implementation of 'virtual fixture', which may provide passive constraint to the motion of the human operator during teleoperation. Virtual fixtures are implemented first by visually, and then haptical fixture was implemented adopting a proprietary Cobot technology. In this preliminary study, it was found that the virtual fixtures could improve accuracy and time for performing the tasks.*

I. INTRODUCTION

During the decontamination and decommissioning (D&D) tasks, human workers are often required to work in confined space with high radioactivity and with incomplete knowledge of the highly complex environment. For such tasks, remote operated robotic systems provide unique means to significantly enhance safety by separating workers from hazardous work areas, as well as provide a strong potential for substantial performance enhancement and cost reduction. However, remote operation, being slow and imprecise, introduces delays in schedule, increases in operation cost and becomes a barrier to deployment. This was evident in a previous deployment of a telerobotic system for dismantling the CP-5 reactor internals at Argonne National Laboratory (Figure 1).

Despite significant improvements in productivity using robots over manual methods, it was observed that nearly 90% of the robotic operation time was spent in tool alignment operations, with the remaining time spent performing actual dismantling operations. For example, during the task of cutting metal pipes or concrete walls with a circular saw as shown in Figure 2, maintaining proper tool alignment is critical in both approaching and cutting phases. In approach phase, it is required to move a tool toward the docking target with predefined orientation. This alignment should be also kept along the cutting path during cutting phase. Due to the poor visual perception and crude manipulation capability of a human operator, performing a cutting task is extremely difficult and time-consuming under teleoperation. In this regard, a significant improvement in task efficiency may be attained if the operator motion can be guided by a virtual fixture.

In this paper, we present an implementation of visually and haptically augmented teleoperation with virtual fixtures, and demonstrate its usefulness for a representative D&D task – cutting a large pipe with a

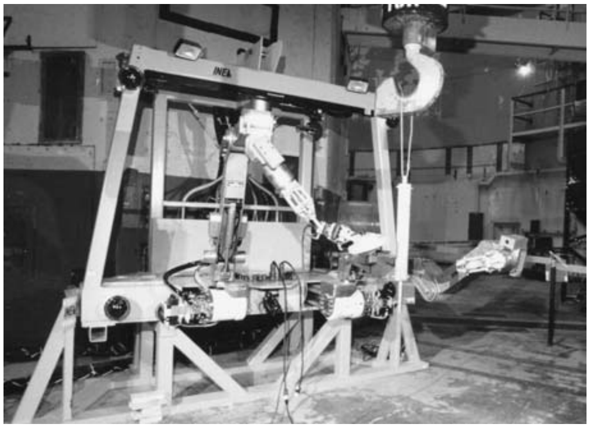


Figure 1. Dual Arm Work Platfom

circular saw. First, we review the characteristics of virtual fixtures needed for various D&D tasks. We then describe implementation and experiments with visual virtual fixtures. We also describe implementation kinesthetic virtual fixtures with 6-DOF Cobotic hand controller, and present preliminary experimental results.

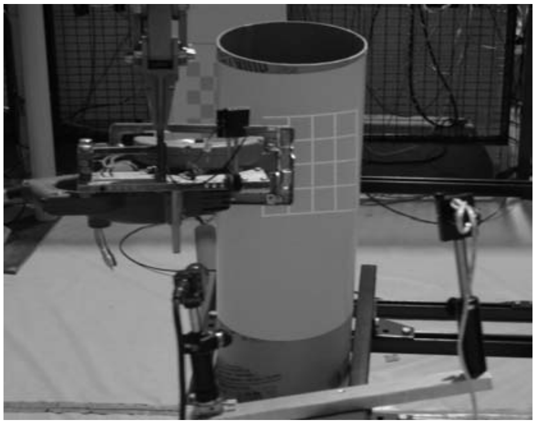


Figure 2. Cutting task with a circular saw

II VIRTUAL FIXTURE

Virtual fixtures can be defined as computer-generated fixtures placed onto the workspace to assist the human operator during the teleoperation [1-4]. These virtual fixtures can be split into two categories based on constraint type: unilateral and bilateral virtual fixtures.

A unilateral virtual fixture has an artificial constraint that expresses an equation of inequality. A unilateral virtual fixture can be thought of as a virtual wall to confine the free motion space. It is also useful to define forbidden regions. As long as the motion is within the unilateral fixtures, meaning it satisfies the inequality constraint, the operator can freely move the slave arm. Figure 3 shows examples of unilateral virtual fixtures.

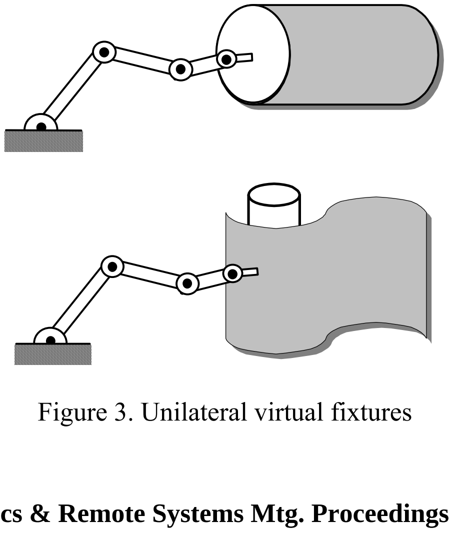


Figure 3. Unilateral virtual fixtures

A bilateral virtual fixture has a bilateral constraint that is expressed with equality. It can be depicted as a virtual slot in which the position of the end-effector is forced to lie as shown in Figure 4. The constraint that the end-effector remains in the slot is always in effect through the slave motion.

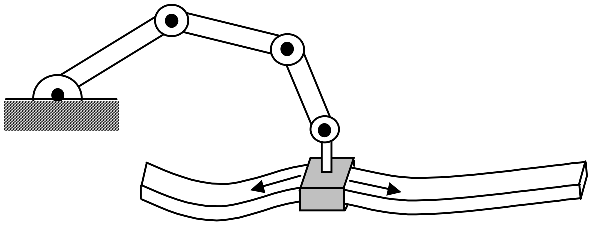


Figure 4. Manipulator moving along the virtual rail

The key concept of bilateral virtual fixtures is that it is suitable to choose the generalized coordinate vector in order to describe the constrained motions. With this generalized space, the motion can be easily decomposed into one in constrained space and the other in free space. Let A represent the instantaneous desired direction of motion along this artificial constraint. From A, a projection matrix, $P = A(A^TA)^{-1}A^T$ can be defined and it projects any vector b onto the column space of A.

$$p = Pb = A(A^TA)^{-1}A^T b.$$

And other projection matrix I-P is the component in the orthogonal complement and it projects any vector b onto the orthogonal complement, which is the left null space, $\aleph(A^T)$. Since I-P is the complement of P, the mapping

$$D = \begin{bmatrix} A(A^T A)^{-1} A^T \\ I - A(A^T A)^{-1} A^T \end{bmatrix}$$

is a bijective (i.e. D is one-to-one and onto). By defining this projection matrix, the master motion is easily decomposed into one in free space and the other in constrained space so that it can confine the master or slave motion along the constrained path.

The type of unilateral virtual fixture used in this experiment is a virtual funnel to guide the cutting tool toward the target pipe during the approach phase as shown in Figure 5. As approaching the target position, the virtual funnel shrinks and the corresponding funnel radius represents how to tolerate the translational deviation from the desired approaching trajectories. As long as the tool remains inside the funnel, it will proceed toward the target position.

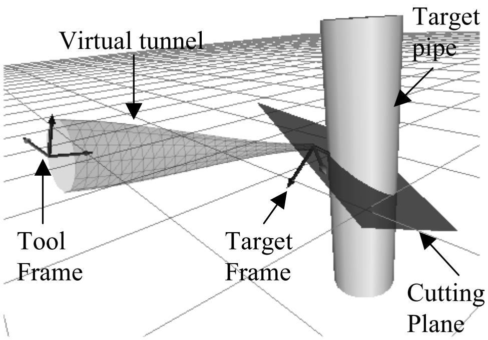


Figure 5. Virtual Funnel

III. VISUALLY AUGMENTED TELEOPERATION

A. Virtual Funnel

The virtual funnel is defined with radius ε_s at the start position p_s, ε_f at the end position p_f, and the tunnel axis $n_t = p_f - p_s$. A cubic function can be used to determine the funnel radius ε_t representing how to tolerate the translational deviation from the desired approach trajectory. The funnel radius ε_t at a given $t \in [0,1]$ is defined as

$$\varepsilon_t(t) = \varepsilon_f + (\varepsilon_s - \varepsilon_f)(2t^3 - 3t^2 + 1).$$

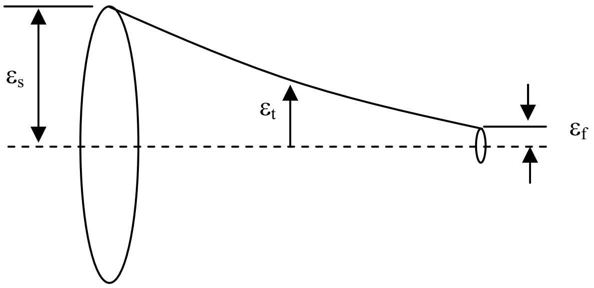
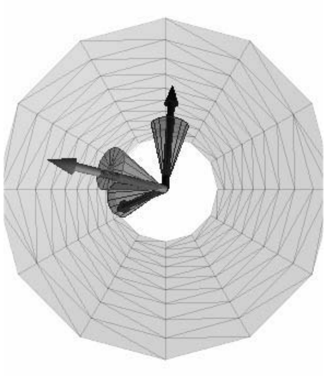


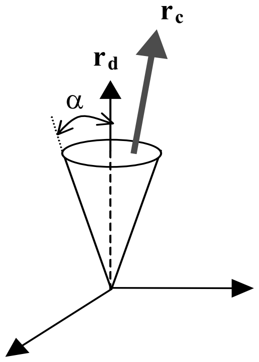
Figure 6. Funnel Geometry

As approaching the target position, the virtual funnel shrinks so that the operator can easily guide the position of tool as shown in Figure 7. The virtual funnel can only be used to assist the translational guidance. In order to assist the operator to align the tool orientation, a virtual aligning cone is created. The virtual cone can be represented as having its vertex at the origin of the tool frame, the axis vector **a** aligned the desired direction vector $\mathbf{r_d}$, and angle α. Since **a** is aligned with $\mathbf{r_d}$, the virtual cone angle α represents how to tolerate the rotational deviation from the desired direction vector. Hence, the operator can get the intuitive perception of the desired rotational motion from this geometrical guidance. Virtual cone can be concisely represented with the introduction of quaternion. With the given start orientation $\mathbf{q_s}$ and the target orientation $\mathbf{q_f}$, the spherical linear interpolation of quaternion at $t \in [0,1]$ yields

$$\mathbf{q_t}(t, q_s, q_f) = (q_0, q) = \{\sin((1-t)\theta)\mathbf{q_s} + \sin(t\theta)\mathbf{q_f}\}/\sin(\theta),$$
$$\text{where } \theta = 2\cos^{-1}(\mathbf{q_s}\cdot\mathbf{q_f}).$$



(a) looking into the funnel



b) virtual alignment cone

Figure 7. Virtual fixture for docking operation

Thus, the centered normal axis vectors of three virtual cones can be defined with orthonormal directional vectors from the following equivalent rotation matrix,

$$\mathbf{R} = [\mathbf{r_{1d}}\ \mathbf{r_{2d}}\ \mathbf{r_{3d}}] = \mathbf{I} + (\sin\phi)\mathbf{S} + (1-\cos\phi)\mathbf{S}^2,$$

where $\phi = 2\cos^{-1}(q_0)$ and $\mathbf{S} = (q/\|q\|)^\wedge$. Figure 7 shows the tool side view of the virtual funnel and cones with the current tool frame.

B. Experiments

Experiments are performed on a telerobotic systems consisting of a Schilling Titan 7F six degree-of-freedom hydraulic driven manipulator and a master input system with magnetic position sensor. Visual virtual funnel is implemented with JAVA 3D in a PC accessing remote distributed objects via Java Remote Method Invocation (RMI) as shown Figure 8.

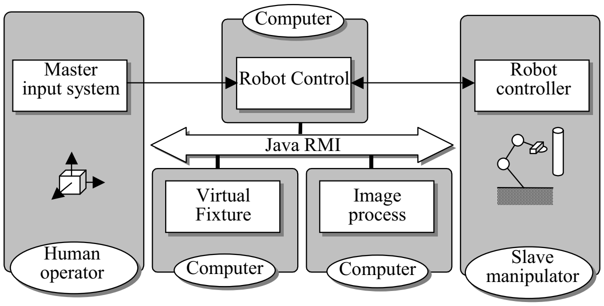


Figure 8. Teleoperation system

To test the virtual funnel, we chose to execute the docking task consisting of approaching and aligning the tool to the target position, which is obtained from a structured light sensor. Figure 9 presents the translational path taken along funnel. It is noticed that even though the operator waggled, he is able to approach to target position. Figure 10 shows the rotational path in terms of roll, pitch, and yaw angles along funnel and the each angle are converged to its target value as approaching.

While the unilateral virtual fixtures provide the augmented geometric information by showing the current position and orientation of tool and the desired instantaneous position and orientation at a given t, a visual cue is implemented for the intuitive guidance with the relevant direction of translation and orientation of the tool frame toward the target frame. For that purpose, a visual navigator consisting of three linear arrows and three circular arrows is implemented as shown in Figure 11. Each arrow gets transparent as the tool comes close to the target position and disappears when the current frame is coincident to the target frame.

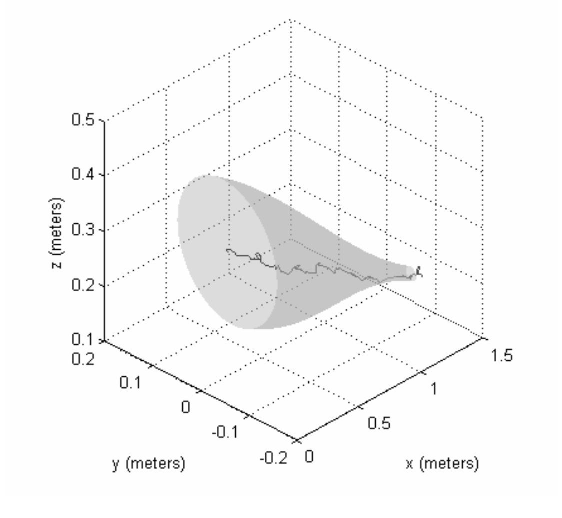


Figure 9. Translational path taken along funnel

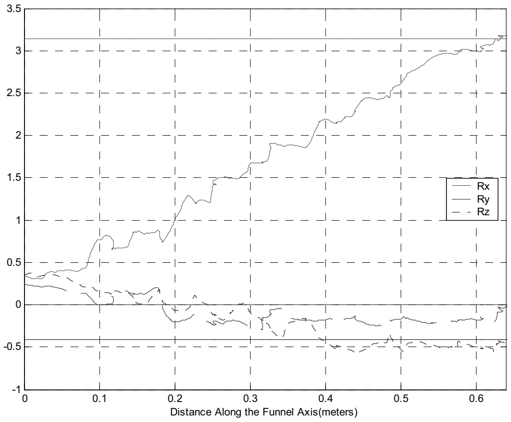


Figure 10. Rotational path along funnel

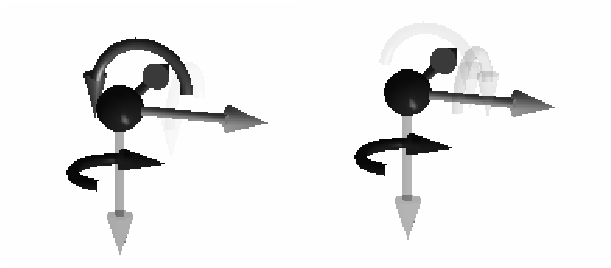


Figure 11. Visual Cue

IV. HAPTICALLY AUGMENTED TELEOPERATION

A. Cobotic Hand Controller

To effectively display the virtual fixture kinesthetically, a new hand controller is developed, based on Cobot technology. Cobot is a proprietary technology capable of providing safe and smooth yet extremely strong constraints through the use of non-holonomic constraints. [5-6] A steered wheel, un-powered about its rolling axis, creates a relationship between the two components of its linear velocity. Higher dimension

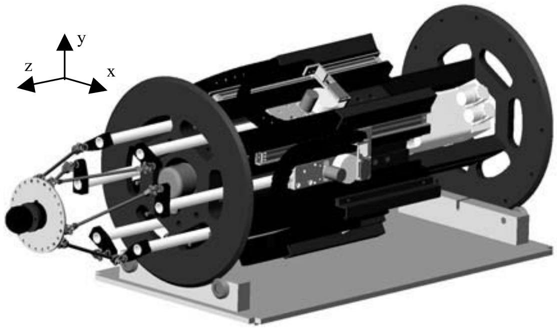


Figure 12. A CAD model of the 6-DOF Cobotic Hand Controller

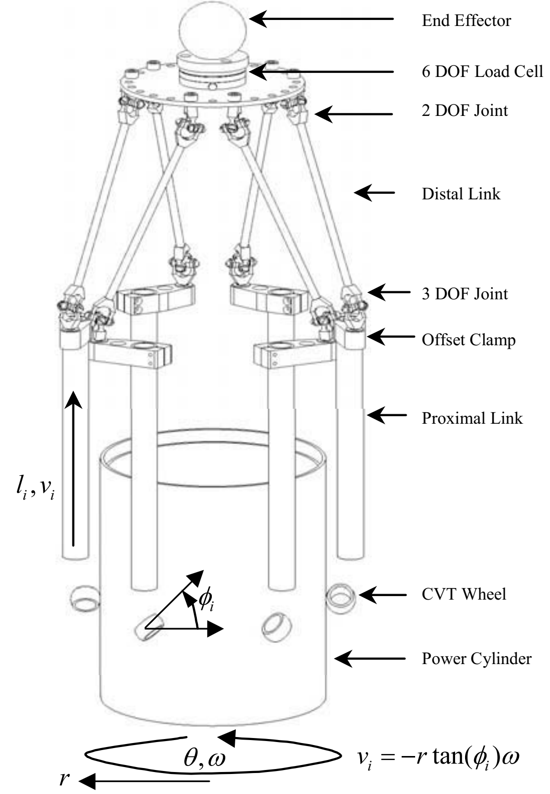


Figure 13. The kinematics of a Merlet-Cobotic parallel platform

cobots utilize varying geometries of rolling contacts. Cobots can either be operated in “free-mode,” where the intent of the operator in the full dimension of the task space is followed completely, or in “virtual-surface” mode, where a lower dimensional surface that the task space guides the operator’s intent tangent to that surface, and the non-holonomic constraints of the rolling wheels, not the torque of any actuators, prevent motion normal to the virtual surface.

The design of this 6-DOF Cobotic Hand Controller utilizes the kinematics of a parallel platform introduced by Merlet [7] (Figure 12 and 13). The proximal links are coupled by three degree-of-freedom universal joints to the distal links, and these in turn are coupled via two degree-of-freedom universal joints to an end-effector platform. A force sensor on the end-effector is used to determine the user’s intent. Our addition to Merlet’s kinematics has been to couple the six linear actuators to a central “power cylinder” through non-holonomic constraints. Linear actuation of the proximal links is achieved via a rotational to linear continuously variable transmission(CVT), namely a steered wheel. The angle of each wheel relates the linear velocity ν_i of each proximal link to the rotational velocity of the power cylinder ω. When the wheels are steered such that their rolling axis is parallel to the power cylinder (ϕ_i=0), a ratio $\nu_I / \omega = -r \tan(\phi_i) = 0$ is set. If the wheels are steered either direction from ϕ_i=0, ratios between ± infinity can be achieved. In practice, wheel slip limits this range. It is also evident, that turning all six wheels to ϕ_i=0 locks the six actuators, and turning them to $\phi_i=\pi/2$ completely decouples the actuators from the cylinder’s velocity, although the cylinder would then be unable to turn.

B. Experimental Operation

To test haptically implemented virtual funnel, we created same unilateral constraint wall to aid the docking task consisting of approaching and aligning the tool to the target position. In Figure 14, a translational trajectory along funnel constraint surface is shown. Once the operator hits the constraint surface, he is able to slide into the target position along the funnel surface. This behavior is contrary to the case of visually augmented teleoperation where the operator tries to keep the current position at the center of funnel. To show the effectiveness of funnel, the operator intended to move around the funnel. Figure 15 shows the rotational path in terms of Euler angles along funnel and the each angle is converged to its target value as approaching.

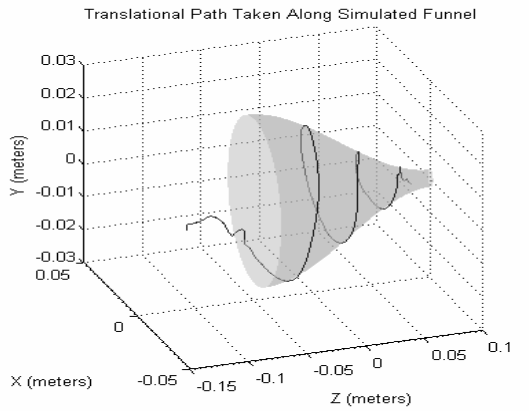


Figure 14. Translational path taken along funnel

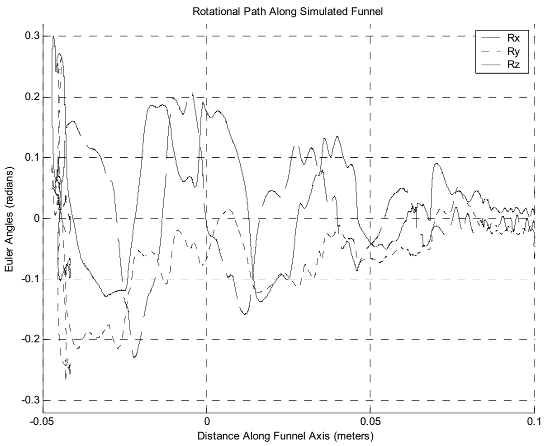


Figure 15. Rotational path taken along funnel

V. CONCLUSION

To enhance the performance of teleoperation in the D&D task, visually and haptically implemented virtual fixtures are developed. Preliminary experimental studies revealed effectiveness of each method. Visually implemented virtual funnel is particularly useful when the tool alignment is needed without the haptic device and a synergistic advantage can be achieved by overlaying with haptically implemented one. Haptically implemented funnel based on new 6-DOF Cobot hand controller certainly enhances the system efficiency by reducing the burden of more concentration on the operator and decreasing the operating time.

ACKNOWLEDGEMENT

This research was sponsored by the Environmental Management Science Program of the Office of Environmental Management and Office of Science, U. S. Department of Energy

REFERENCES

1. P. Marayong, M. Li, A. Okamura, and G. Hager, “Spatial motion constraints: Theory and demonstrations for robot guidance using virtual fixtures,” In Proc. IEEE International Conference on Robotics and Automation, pp. 1954 -1959, 2003
2. Bettini, S. Lang, A. Okamura, and G. Hager, Vision assisted control for manipulation using virtual fixtures,” In Proc. IEEE/RSJ International Conference on Intelligent Robots and Systems, pp. 1171-1176, 2001
3. Moore, M.A. Peshkin, and J.E. Colgate, “Cobot Iplementation of virtual paths and 3-D virtual surfaces,” IEEE Transactions on Robotics and Automation, Vol. 19, pp. 347-351, 2003
4. L.D. Joly and C. Andriot, “Imposing motion constraints to a force reflecting telerobot through real-time simulation of a virtual mechanism,” In Proc. IEEE International Conference on Robotics and Automation, pp. 357-362, 1995
5. M.A. Peshkin, J.E. Colgate, W. Wannasuphoprasit, C.A. Moore, R.B. Gillespie, and P. Akella, “Cobot architecture,” IEEE Transactions on Robotics and Automation, Vol. 17, pp. 377-390, 2001
6. E.L. Faulring, J.E. Colgate, and M.A. Peshkin, “A high performance 6 DOF haptic cobot,” submitted to IEEE International Conference on Robotics and Automation, 2004
7. J.P. Merlet, “Direct kinematics and assembly modes of parallel manipulators,” International Journal of Robotics Research, Vol.11 pp.150-162, 1992