# ON THE DESIGN OF LARGE SCALE REDUNDANT PARALLEL MANIPULATOR


**Wu huapeng, Heikki handroos and Juha kilkki**

*Machine Automation Lab, Lappeenranta University of Technology*
*LPR-53851 Finland*
*huapeng@lut.fi, handroos@lut.fi, kilkki@lut.fi*



Abstract: This paper presents a large scale redundant parallel manipulator. To design the manipulator some preliminary considerations are given. The manipulator is built based on two 3DOF parallel mechanisms. Hydraulic cylinders are employed as actuators to achieve linear motion and offer great force. The kinematics analysis is given for the manipulator. The control schemes are discussed in the paper and the simulation results are presented.


Keywords: Parallel manipulator, design method and kinematics analysis.


## 1.INTRODUCTION

Recently most of rock drill machines are designed in serial linker. The tool holder is always very heavy since drill tools are very long. During drilling process the manipulator vibrates very much due to the low stiffness of manipulator and great drilling force, and this causes some problems such as the tools broken and big inaccuracy. To improve stiffness of those kinds of manipulators, parallel mechanism can be considered.

Parallel manipulators have found widely application in industrial robots in the last few years, because they have many substantial advantages compare with conventional serial linker manipulators, such as higher stiffness, higher accuracy, and improved dynamic characteristic [1][2][3]. The typical parallel manipulator is so call Stewart platform (Stewart 1965) has been studied in many literatures [4][5].

In this paper we present a design procedure for a redundant parallel manipulator for the drilling task. The manipulator is considered that at lest it has same workspace as the types used today, but more strongly without increase very much weight.

## 2.PRELIMINARY CONSIDERATION

The rock drill machines are used in tunnel or in mine to make hole. Since the work conditions always are very hard and environments are very complex, the manipulators have to be made very stronger, suitable operative and enough workspace capability. In order to save the drill tool, the vibration should be limited as small as possible. That means the manipulators should have high stiffness. To design the manipulator the follow preliminary problems are considered.

Workspace: Basically we hope the workspace capability of the manipulator can be as big as possible, in tunnel or in mine it is impossible for more drilling machines work together because the smaller room. The big workspace capability manipulator can fit different size tunnel, but unfortunately big workspace capability means large size or more linkages are need for the manipulator, this will reduce the stiffness of manipulator and causes some problems such as vibration, and so on. The suitable workspace is A=45m╳ m, and this workspace is required for our parallel manipulator.

Stiffness: The stiffness is very important for the manipulator. It is one important critical condition for us to design the manipulator. Normally the arms of manipulator are designed by using light material to reduce the weight of manipulator, however once the payloads are very heavy the compliance of manipulator will increase. Nowadays the deformation errors of rock manipulators are always bigger than ± 20 mm at end effector, and vibrations are also very big because the low stiffness of manipulators. To increase the stiffness of manipulators, it is more suitable to use parallel structure than to use stronger material, which will make manipulator high cost and difficult to be machined. The branches of parallel mechanism can be considered to use hydraulic actuators, since hydraulic cylinder can offer linear motion and great force.

Collision avoiding: Normally, five degrees freedoms are need for rock drill process. As the environment is very complex in rock drilling, more than five degree freedoms for manipulator are suggested, so that the manipulator has the ability of avoiding collision. Usually, the collision happens between the end-effector and manipulator itself, duo to the longer length of end-effector. So multi-degree redundant manipulator is considered.

Control scheme: The control scheme can be alternative in two algorithms: manul-operation and auto-operation. In manul-operation one or more joysticks are need to control all the cylinders. In auto-operation all the position and orientation of the holes can be got from drilling process planning program. And the drilling process will execute automatically under the computer control.

## 3.COMONENTS DESIGN

For the above propose a redundant parallel manipulator is presented in Fig.1, This manipulator consists of 7 drivers (six hydraulic cylinders and one revolute hydraulic driver) based on two 3DOF parallel mechanisms. In the first stage the telescopic beam is connected to basement by a universe joint while it is fixed with mid plate. In the second stage the telescopic beam is fixed with mid plate and connected the end plate by a universe joint. So the first stage similar to an arm and can be extended, the second stage looks like a wrist and can be extended too. Universe joints are employed in the manipulator for all the hydraulic cylinder connections.

Fig.1 Parallel manipulator

The special character of the manipulator is that the end effector is very long. The long length of end effector will limit the workspace of manipulator, So an addition revolute actuator is used to enlarge the workspace and to make the motion of manipulator more nimble.

### *3.1 Hydraulic cylinder*

Hydraulic cylinders are employed in parallel mechanism since they can offer great force and linear motion. To design cylinder some condition should be considered, firstly the cylinder should offer enough forces under maximum pressure, and the maximum pressure in drill system is about 160bar. This parameter can be used to calculate the diameters D and d of cylinder, the push force of cylinder is

$$F = P1 \cdot \frac{\pi D^2}{4} - P2 \cdot \frac{\pi (D^2 - d^2)}{4} \tag{1}$$

Where, P1 is pressure of blind chamber,

P2 is pressure of rod chamber,

And draw back fore is

$$f = P2 \cdot \frac{\pi (D^2 - d^2)}{4} - P1 \cdot \frac{\pi D^2}{4} \tag{2}$$

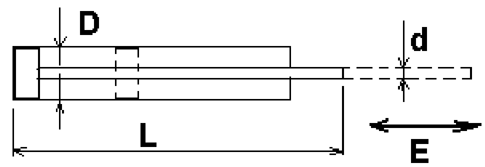



Fig .2 Hydraulic cylinder

Secondly, the workspace is mainly determined by the length and extension of cylinder and their configure size in manipulator. The cylinder should offer enough length and extension so that the manipulator can achieve required workspace. All the cylinders have same sizes in length and assemble in symmetrical configuration. As show in Fig.3 the big size of **B**, small size **L** and **e** will make manipulator stronger but smaller workspace. The parameter **B** is also constrained by the space on which manipulator will be mounted. Actually bigger **B** will cause huge structure of manipulator, in this case **B** is limit less than one meter, then in order to reach the required workspace, the suitable parameter **L** can be determined.

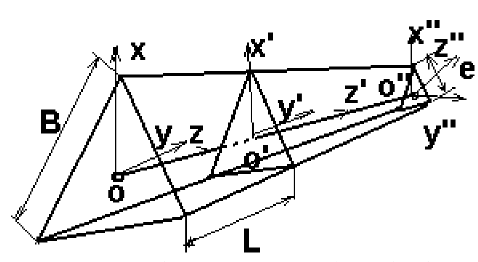



Fig. 3 structure of manipulator

Thirdly, the cylinder should satisfy the bulking condition. As the downside cylinders in manipulator always sustain the compressive force as shown in Fig.4.

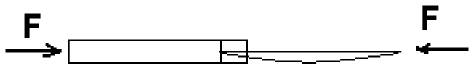



Fig. 4 Bulking of cylinder

The critical buckling load is given by Euler equation

$$F = \frac{\pi^2 EI}{L^2} \tag{3}$$

Where, E is the modulus of elasticity,
I is the moment inertia of rod.

From Euler equation we can see that the length L and diameter d determine the bulking condition of the cylinder. So to determine all the parameter of cylinder, the condition of force, workspace, and bulking critical should be considered synthetically.

### 3.2. *Joints design*

All the connecting joints in this manipulator are universe joints. The joints that connect the telescopic beam to the platform should be designed to take great force and offer enough rotary angle, since they strongly influence the stiffness and workspace of manipulator. To design the universe joints finite analysis method is used. The structure of universe joint is illustrated in Fig. 5, those universe joints can offer rotary angles about two vertical axes, and the ranges of angles are $\pm\ 50^0\ and \pm\ 90^0$.

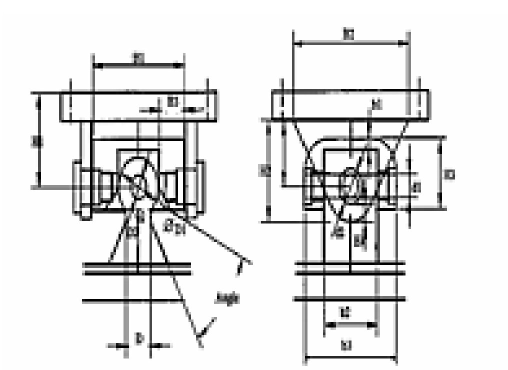


Fig.5 Universe joint

### 3. 3 *Telescope beam*

Unlike normal parallel manipulator this parallel manipulator is one type of telescopic beam based, the main advantage this kind structure is that the twist toque is taken by the telescopic beam not by the cylinders. In the Stewate structure the cylinder can take the twist toque but the structure is complex and workspace is small. The structure of beam is illustrated in Fig.6.

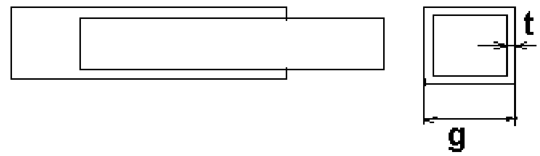



Fig.6 Telescopic beam

The telescopic beams are standard components; the parameter **t** and **g** are determined by how much force they can take with in the limit deformation. The sliding bearings are used between the two components, and the length of the beam mast satisfies the maximum extension of manipulator.

### *3.4 Rotary actuator*

The rotary actuator is one kind of combined module, it mainly consist of one cylinder and a translation-to-rotation converter. The main requiring of the actuators are offering enough toque and rotary angle that must be great than 360 degree.

## 4.KINEMATICS ANALYSIS

The kinematics analysis of the manipulator is based on matrix and geometry method, including forward kinematics analysis and inverse kinematics analysis. The forward kinematics analysis is for the given parameters of cylinders to find the position of end-effector, which can be used, in simulation and workspace capability analysing. The inverse kinematics analysis is for given position of end-effector to find the parameters for the entire cylinders, which can be used in control of manipulator. The co-ordinate systems are built for kinematics analysis as shown in Fig.3.

### 4.1 *Forward kinematics analysis*

The forward kinematics is find position of end-effector for given parameters of actuator. In our manipulator it is difficult to find the solution directly since the structure is very complex. Firstly we solve forward solution based on the parameters of telescopic beam and parameters of joints, and then find the relations between those parameters and parameters of cylinders.

The forward kinematics problem can defined as

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = T1 \cdot T2 \cdot \begin{bmatrix} x_p'' \\ y_p'' \\ z_p'' \\ 1 \end{bmatrix} \tag{4}$$

where $x_p'', y_p'', z_p''$ are the coordinates of end – effector with respect to the frame $x''y''z''o''$,

x, y, z are the coordinates of end-effector with respect to the frame xyzo,

T1 and T2 are the transform matrixes of two stages parallel mechanisms.

T1,T2 are defined in the terms of the length of telescopic beams and the angles of joints:

$$T1 = \begin{bmatrix} c\beta_1 & s\beta_1 \cdot s\gamma_1 & s\beta_1 \cdot c\gamma_1 & L_1 s\beta_1 \\ 0 & c\gamma_1 & -s\gamma_1 & -L_1 c\beta_1 \cdot s\gamma_1 \\ -s\beta_1 & c\beta_1 \cdot s\gamma_1 & c\beta_1 \cdot c\gamma_1 & L_1 c\beta_1 \cdot c\gamma_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{5}$$

$$T2 = \begin{bmatrix} c\beta_2 & s\beta_2 \cdot s\gamma_2 & s\beta_2 \cdot c\gamma_2 & 0 \\ 0 & c\gamma_2 & -s\gamma_2 & 0 \\ -s\beta_2 & c\beta_2 \cdot s\gamma_2 & c\beta_2 \cdot c\gamma_2 & L_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{6}$$

And

$$\begin{bmatrix} xp'' \\ yp'' \\ zp'' \\ 1 \end{bmatrix} = \begin{bmatrix} -Rs\phi \\ Rc\phi \\ Le \\ 1 \end{bmatrix} \tag{7}$$

where, c = cos, s = sin,

$\beta_1, \gamma_1$ Are the angles about the y'' and the x'' axes.

$\beta_2, \gamma_2$ Are the angles about the y and the x axes.

$L_1, L_2$ Are the lengths of telescopic beam of two parallel mechanisms.

$L_e, R$ Are the lengths of rotary arm and beam of end-efector, those two parameters are always constant.

$\phi$ is the angle of rotary actuator about $z''$ axis.

Substitute equations (7) (6) (5) into equation (4), the position of end-effector can be found by giving the parameters $\beta_1, \gamma_1, \beta_2, \gamma_2, L_1, L_2$ and $\phi$ . And the orientation of end –effector are

$$\beta = \beta_1 - \beta_2 ; \gamma = \gamma_1 - \gamma_2 . \tag{9}$$

Up to now the forward problem seams to be solved, but we hope to find the relations with the parameters of cylinders. According to the structures of parallel mechanism the relationships between the lengths of cylinder and $\beta_1, \gamma_1, \beta_2, \gamma_2, L_1, L_2$ can given by

$$\begin{cases} l_{11}^2 = (m1 - m2 \cdot c\gamma_1 + L_1 \cdot s\gamma_1)^2 \\ \quad + (-m1/\sqrt{3} + m2/\sqrt{3} \cdot c\beta_1 - m1 \cdot s\beta_1 \cdot s\gamma_1 - L_1 \cdot s\beta_1 \cdot c\gamma_1)^2 \\ \quad + (m2/\sqrt{3} \cdot s\beta_1 + m2 \cdot c\beta_1 \cdot s\gamma_1 + L_1 \cdot c\beta_1 \cdot c\gamma_1)^2 \\ l_{12}^2 = (m1 + m2 \cdot c\gamma_1 + L1 \cdot s\gamma_1)^2 \\ \quad + (-m1/\sqrt{3} + m2/\sqrt{3} . c\beta_1 + m2 \cdot s\beta_1 \cdot c\gamma_1 - L_1 \cdot s\beta_1 \cdot c\gamma_1)^2 \\ \quad + (m2/\sqrt{3} \cdot s\beta_1 - m2 \cdot c\beta_1 \cdot s\gamma_1 + L_1 \cdot c\beta_1 \cdot c\gamma_1)^2 \\ l_{13}^2 = (L_1 \cdot s\gamma_1)^2 \\ \quad + (2 \cdot m1/\sqrt{3} - 2 \cdot m2/\sqrt{3} \cdot c\beta_1 - L_1 \cdot s\beta_1 \cdot c\gamma_1)^2 \\ \quad + (L_1 \cdot c\beta_1 \cdot c\gamma_1 - 2 \cdot m2/\sqrt{3} \cdot s\beta_1)^2 \end{cases} \tag{10}$$

And

$$\begin{cases} l_{21}^2 = (m2 - m3 \cdot c\gamma_2)^2 \\ \quad + (-m2/\sqrt{3} + m3/\sqrt{3} \cdot c\beta_2 - m3 \cdot s\beta_2 \cdot s\gamma_2)^2 \\ \quad + (m3/\sqrt{3} \cdot s\beta_2 + m3 \cdot c\beta_2 \cdot s\gamma_2 + L_2)^2 \\ l_{22}^2 = (-m2 + m3 \cdot c\gamma_2)^2 \\ \quad + (-m2/\sqrt{3} + m3/\sqrt{3} \cdot c\beta_2 + m3 \cdot s\beta_2 \cdot s\gamma_2)^2 \\ \quad + (m3/\sqrt{3} \cdot s\beta_2 - m3 \cdot c\beta_2 \cdot s\gamma_2 + L_2)^2 \\ l_{23}^2 = (2 \cdot m3/\sqrt{3} - 2 \cdot m3/\sqrt{3} \cdot c\beta_2)^2 \\ \quad + (-2 \cdot m3/\sqrt{3} \cdot s\beta_2 + L_2)^2 \end{cases} \tag{11}$$

Where, m1, m2, m3 are the lengths of sides of each three triangular plates.

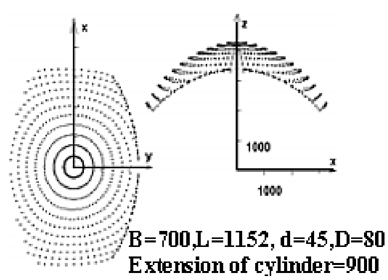



Fig.7 workspace

From (4) to (11) we can determine the workspace of manipulator. Fig.7 shows the workspace of one manipulator.

4.2 *inverse kinematics*

Inverse kinematics problem is to find the all the parameters of actuator for the giving position and orientation of the end-effector. In our manipulator, the inverse kinematics problem is to find all the parameters for all the hydraulic cylinders at giving position and orientation of end-effector. It's defined as

$$\mathbf{q}=\lambda\ (\mathbf{p}) \qquad (12)$$

Where, $\mathbf{p}=(x, y, z, \beta, \gamma)^t$ is the vector of the position and orientation of the end effector with respect to the base co-ordinate system xyzo.

$\mathbf{q}=(l_{11}, l_{12}, l_{13}, l_{21}, l_{22}, l_{23}, \phi)^t$ is the vector of the actuators, $l_{ij}$ (I=1,2; j=1,2,3) are the length of cylinders and $\phi$ is the angle of the rotary actuator with respect to z" axis.

In equation (12) the vector **p** is a 5×1 vector, and vector **q** is a 7×1 vector. This means there are two redundant degrees in our manipulator, and make equation (2) more difficult to be solved. We can resolve equation (12) into following two steps

$$\mathbf{q} = \mu\ (\mathbf{r}) \qquad (13)$$

$$\mathbf{r} = h\ (\mathbf{p}) \qquad (14)$$

Where, $\mathbf{r} = (L_1, L_2, \beta_1, \gamma_1, \beta_2, \gamma_2, \phi)^t$.

And equation (13) is defined by equation (10) and equation (11). So the inverse kinematics problem becomes to solve equation (14). In order to solve the equations (13) and (14), the optimal method is used, which is to achieve the minimum deflection of manipulator at a certain position of end-effector. The optimisation problem is defined as the object function, which minimise the deflection of manipulator.

$$\text{Min } f(\mathbf{r}) \qquad (15)$$

And subject to the constraints of avoiding collision condition

$$v_i(r) \leq 0 \qquad (16)$$

Joints limit

$$\min \beta_i, \gamma_i \leq \beta_i, \gamma_i \leq \max \beta_i, \gamma_i \text{ (i=1,2)} \qquad (17)$$

And limit of cylinders

$$\min l \leq l_{ij} \leq \text{miax } l \text{ ( i=1,2; j=1,2,3)} \qquad (18)$$

To solve the optimisation problem, one evolution search method is employed. Therefore, the inverse kinematics solution can be found in real-time control.

## 5.SYSTEM CONTROL

The control method of manipulator is alternative, manul-operation and auto-operation. Both of the methods are using closed-loop control for all the actuators. The closed-loop control system includes hydraulic cylinder, position sensors, servovalve, and computer (shown in Fig.8)

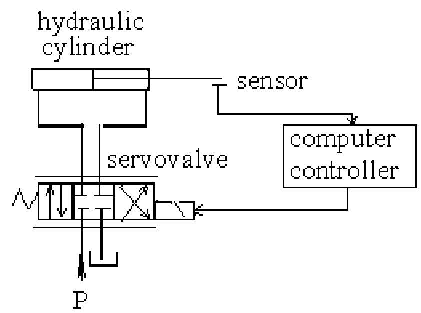



Fig.8 closed-loop control

### 5.1 *Control scheme*

The difference between manu-operation and auto-operation is that they use difference inputs. In manu-operation the joystick or keyboard is used to input the parameters of position and orientation to the computer. However, in auto-operation the datum of position and orientation are got from task planning processor, which is a program plans the trajectory of manipulator for drilling task and control the drilling process of the manipulator automatically. The structure of whole control system is illustrated in Fig.9.

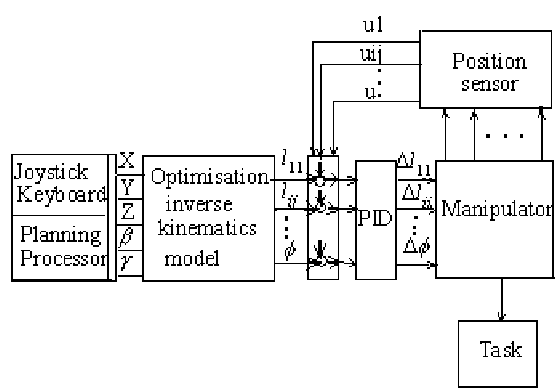
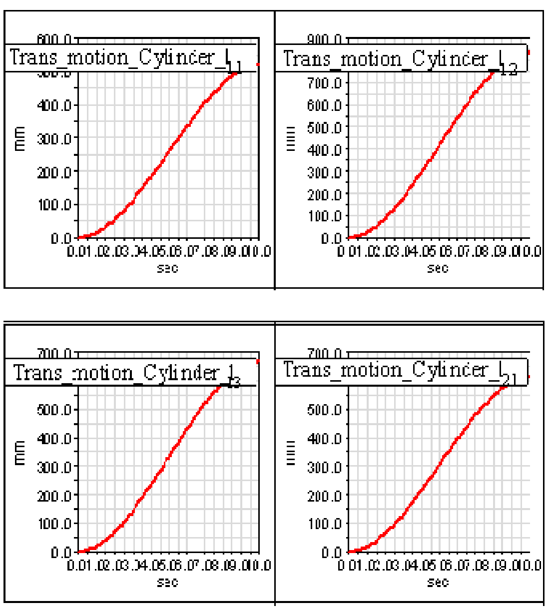


Fig.9 Control structure

Actually this structure is an open-loop control scheme for entire manipulator, since it is impossible to measure the position and orientation of end-effec in the drilling situation. Only the closed-loop controls are introduced to hydraulic cylinder actuator. That is why we employ the optimisation method to achieve the minimum deflection in inverse kinematics model, so that in any position the manipulator will take as higher stiffness as possible.

### *5.2 Simulate results*

We built simulate model of manipulator in ADAMS software, and control programs including inverse kinematics model are designed in C++ language. The process includes four steps: input data (position and orientation), calculate control parameters by control program, translate the parameters to ADAMS model, and simulate in ADAMS. The Fig.10 are shown simulate results. The position and orientation for the ene-effector is (692,1600,5500,0,0), to generate the motion of cylinder, cubic polynomial function is used, so that the motion of end-effector is smooth from one point to another point.



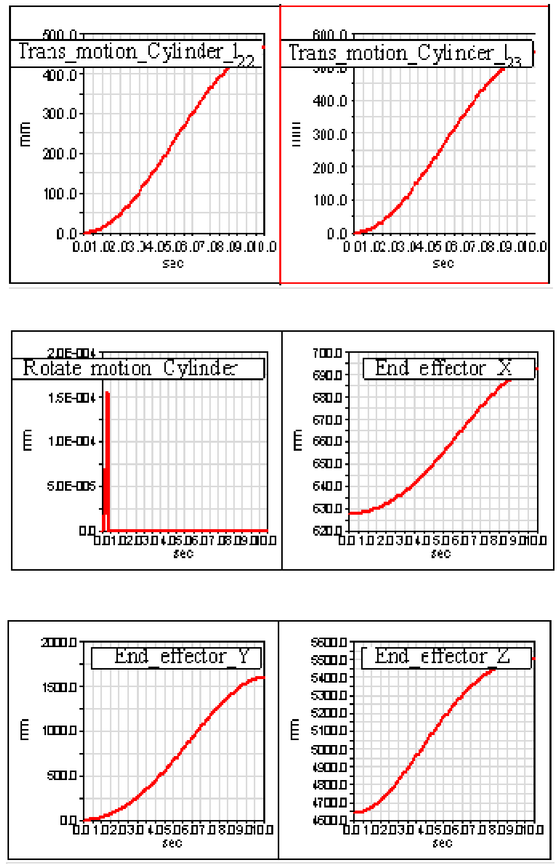




Fig.10 Simulation results

## 6. CONCLUSIONS

A large-scale 7-DOF parallel redundant manipulator has been developed. To design the manipulator some Preliminary problems were considered, such as stiffness, workspace, operation ability, and collision avoiding. Some design method for the key components of manipulator was presented. The kinematics model was discussed. The control structure was built. And the simulate result were given by means of ADAMS model.

## REFERENCE


[1] D.Chakarov and P.Parushev ,Synthesis of parallel manipulators with linear drive modules. Mech. Meach. Theory Vol.29,No.7 pp.917-932,1994.

[2] G.R.Dunlop,T.P.Jones Position analysis of a two DOF parallel mechanism-the canterbury traker. Mech. Mach. Theory 34(1999) 399-614.

[3] P.Kallio M.Lind Q.Zhou H.Koivo A 3 DOF Piezohydraulic parallelhua micromanipulator.

Proceeding of the 1998 IEEE Internation Conference Robotics & Autimation
[4] D.Stewart, Proc. of the Institution of Mechanical Engineers(London),Vol.180,Part1,(1965).
[5] C.C.Nguyen, F.J.Pooran, Dy namic analysis of a 6 DOF CKCM robot end-effector for dual-arm telerobot system. Robotics and autonomous systems. 5(1989)377-394.