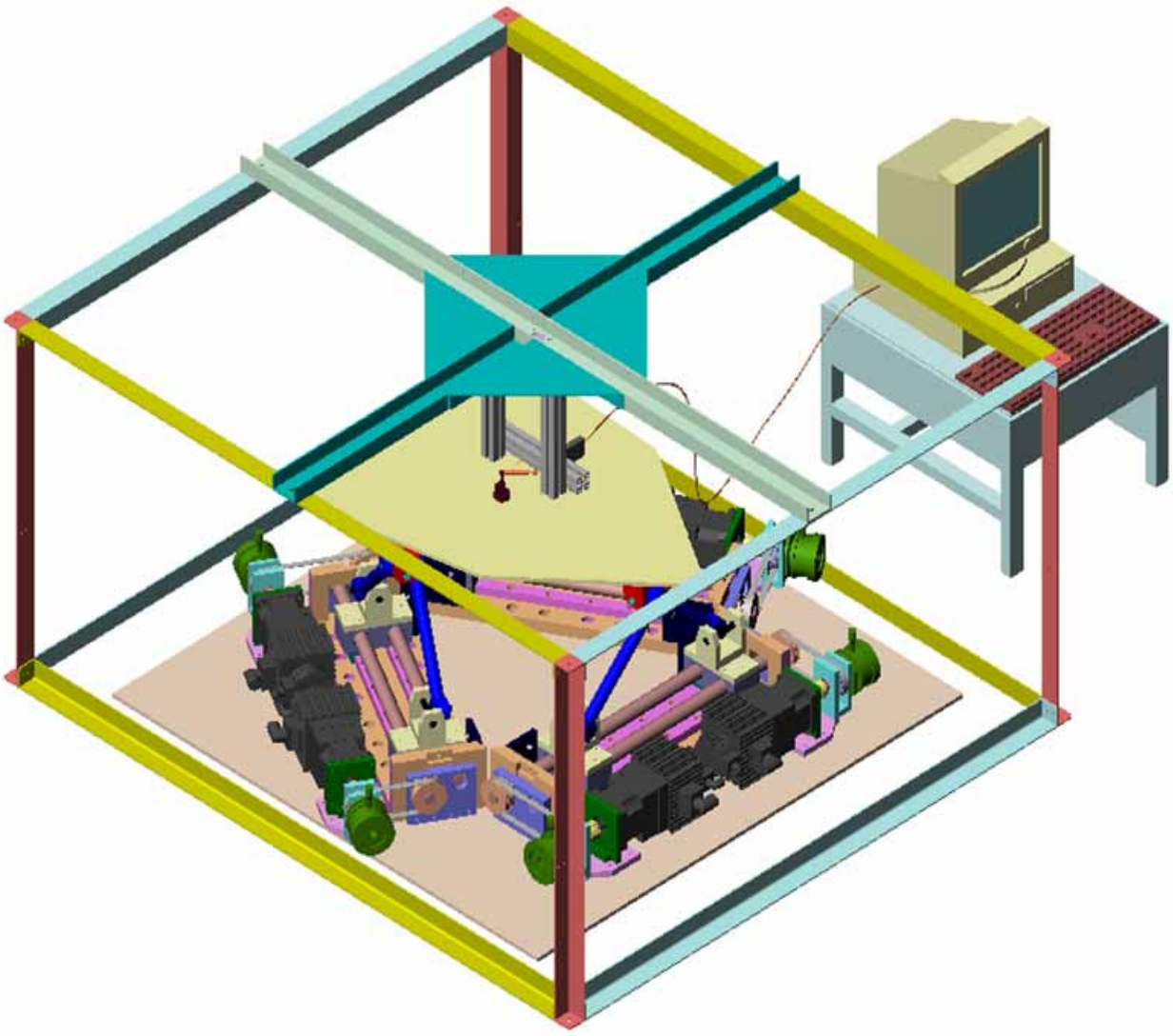


Figure. 4.1 Configuration of the error diagnosis experiment

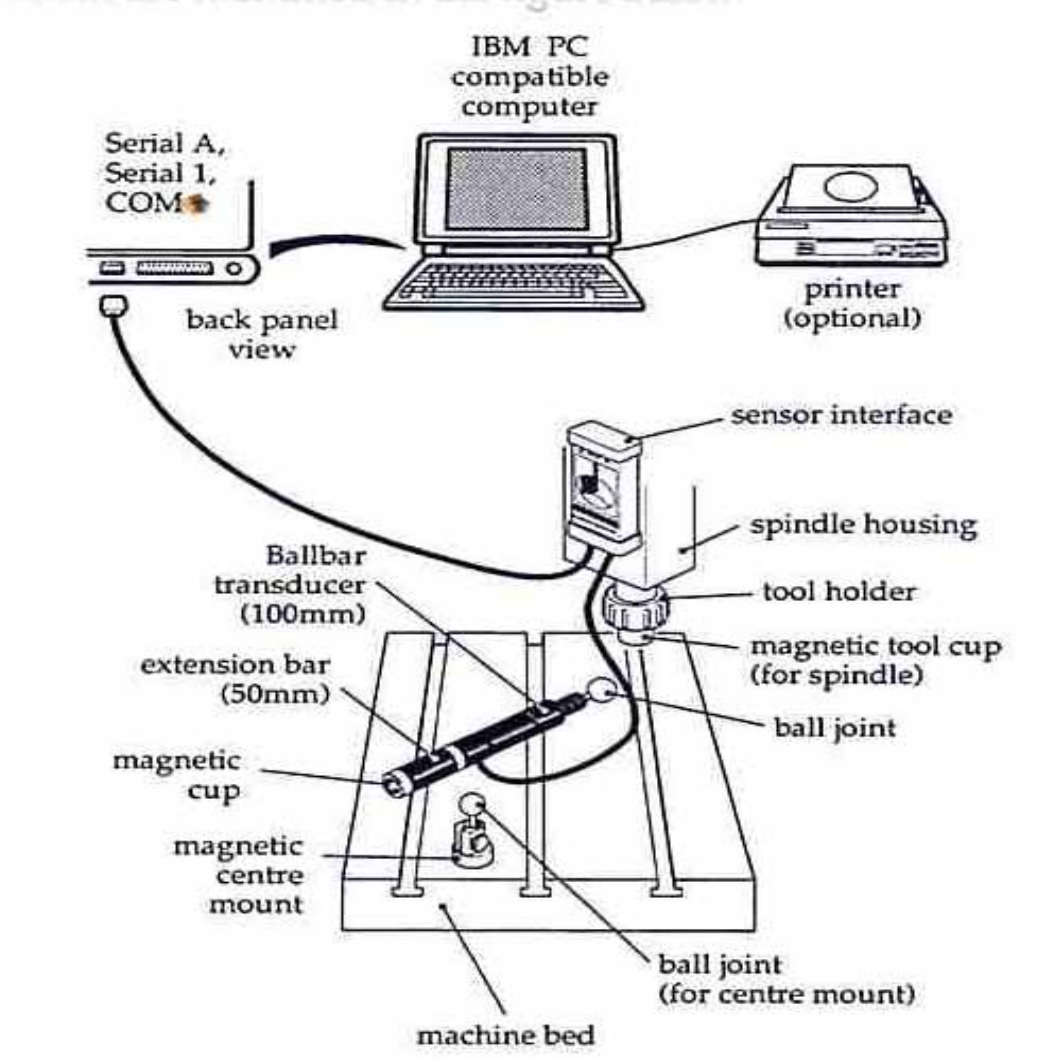


Figure 4.2 Double Ball Bar system

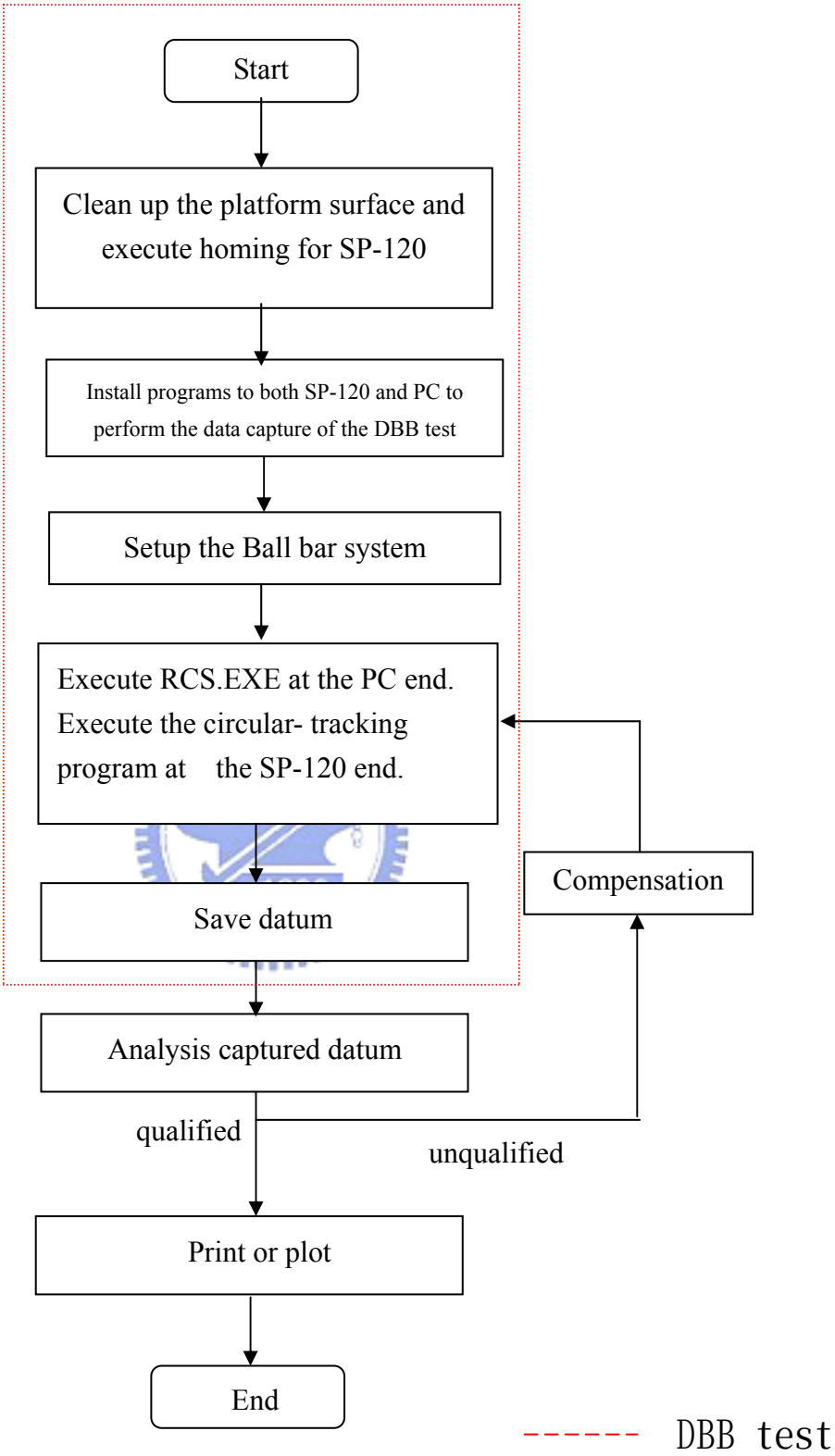


Figure 4.3 Procedures of DBB test & error diagnosis

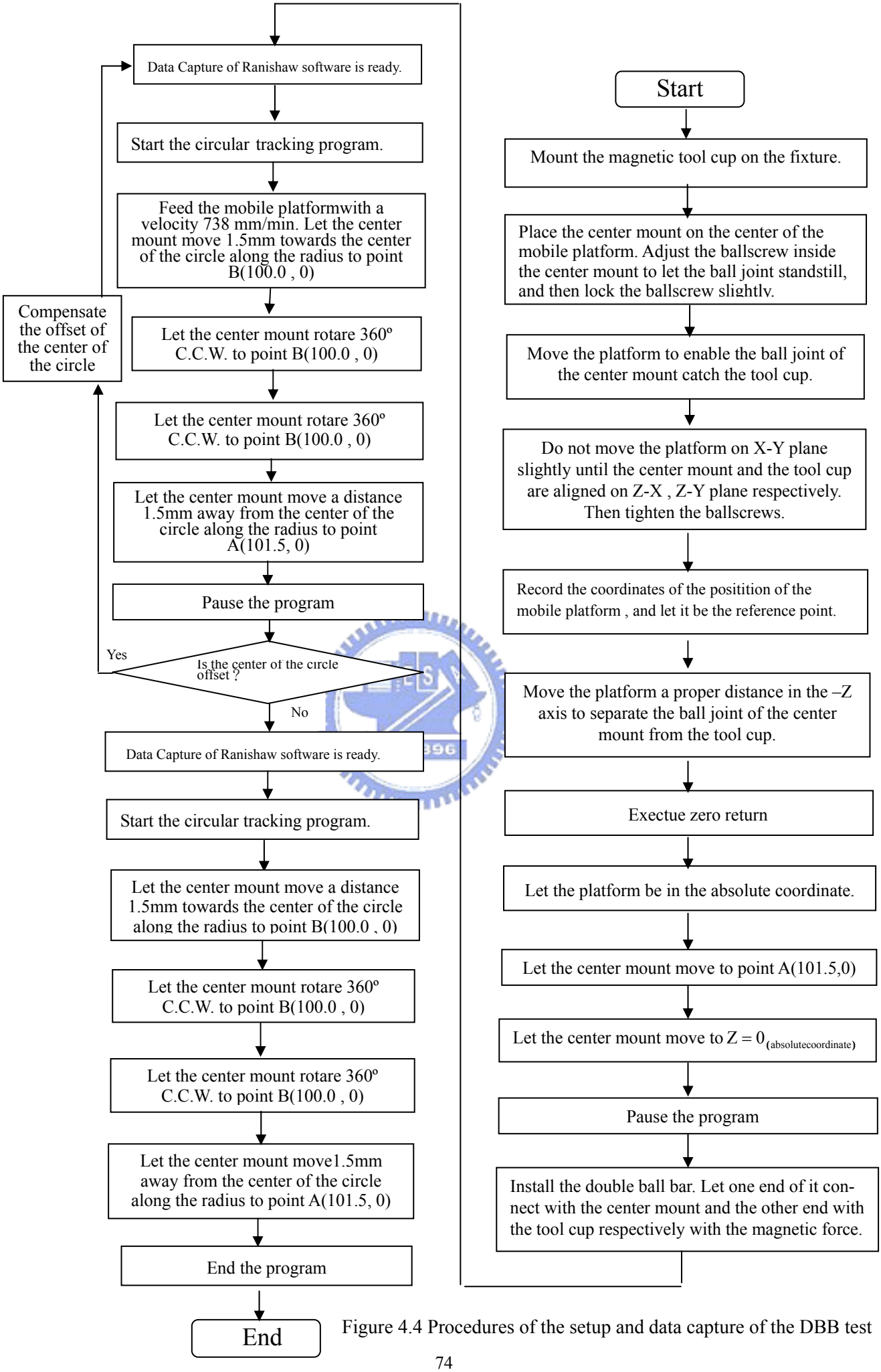


Figure 4.4 Procedures of the setup and data capture of the DBB test

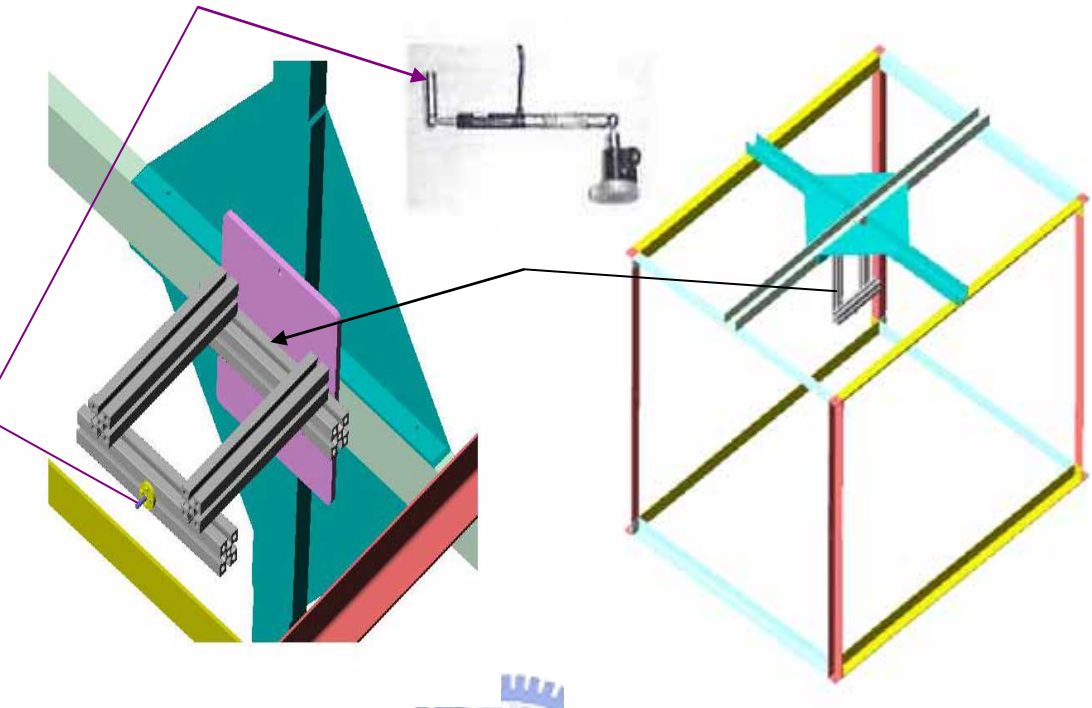


Figure 4.5 Design of the auxiliary fixture for DBB test

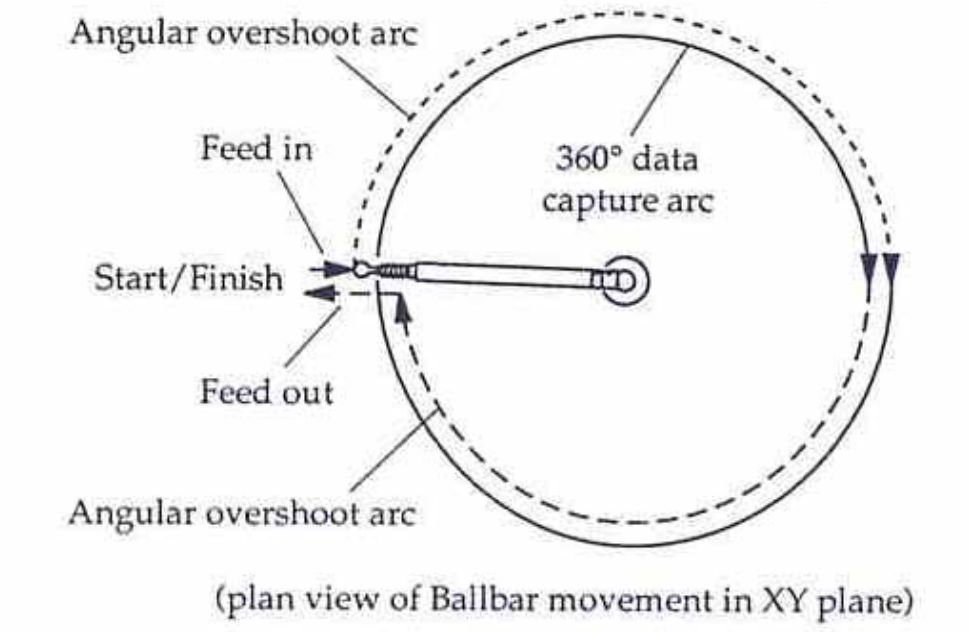


Figure 4.6 Testing path of the circular contour tracking

Figure 4.7 The completed setup of the DBB system

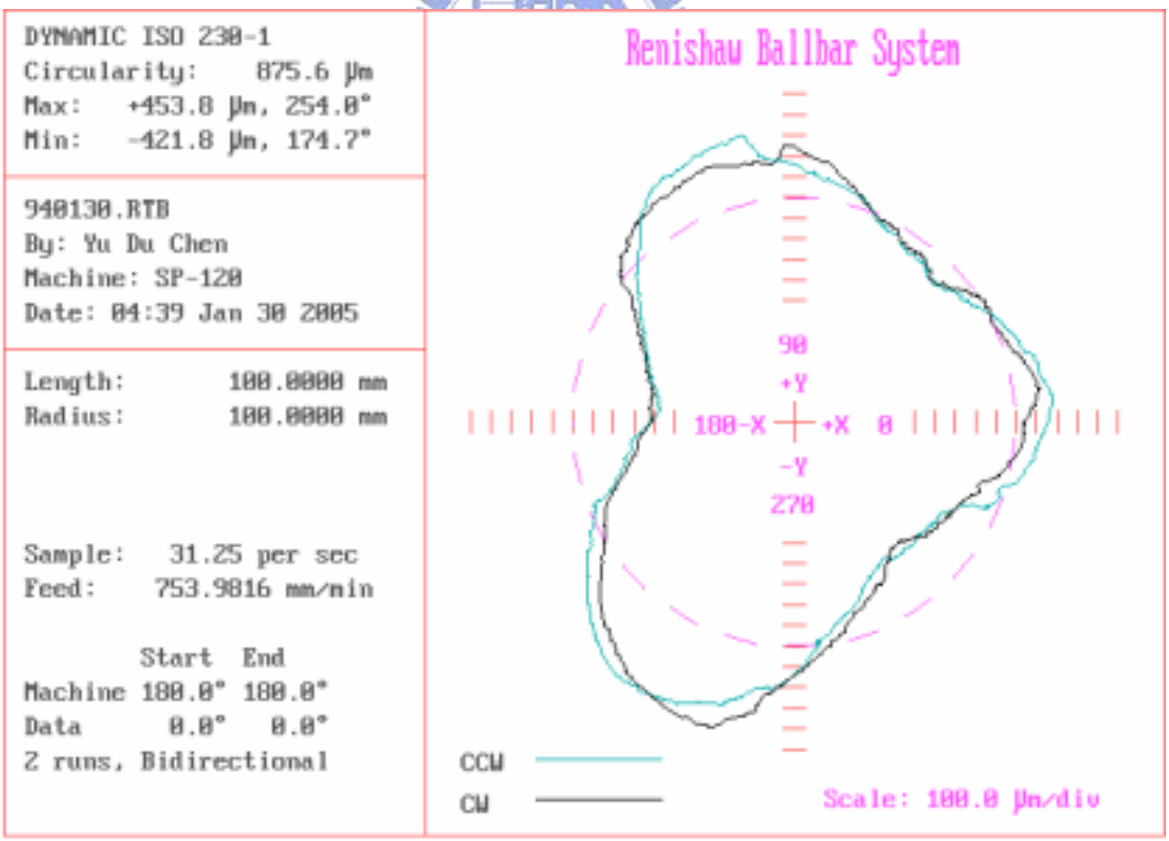


Figure 4.8 Polar plot obtained from the data captureof DBB test

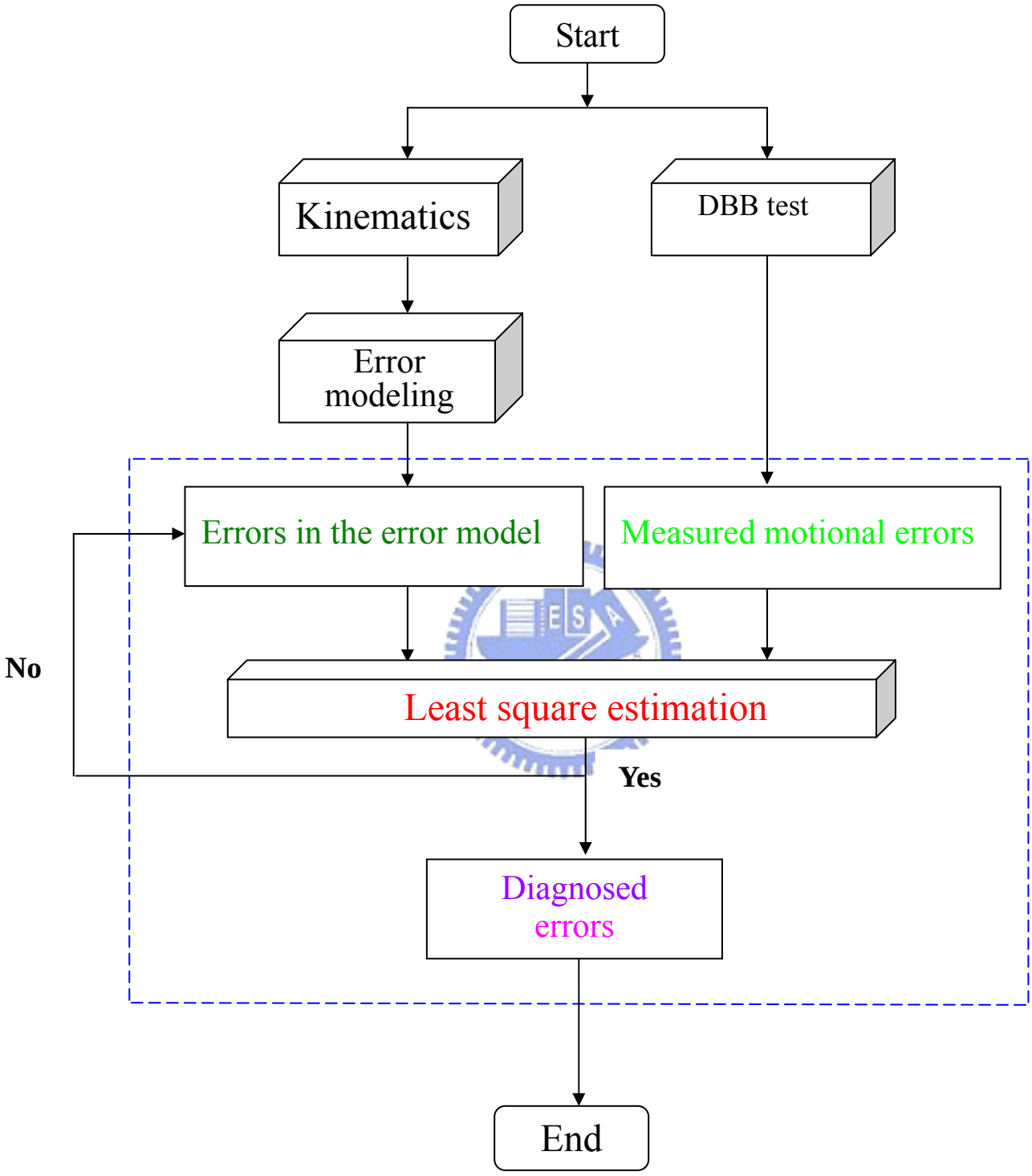


Figure 5.1 Procedures of Curve Fitting with Least Square Estimation

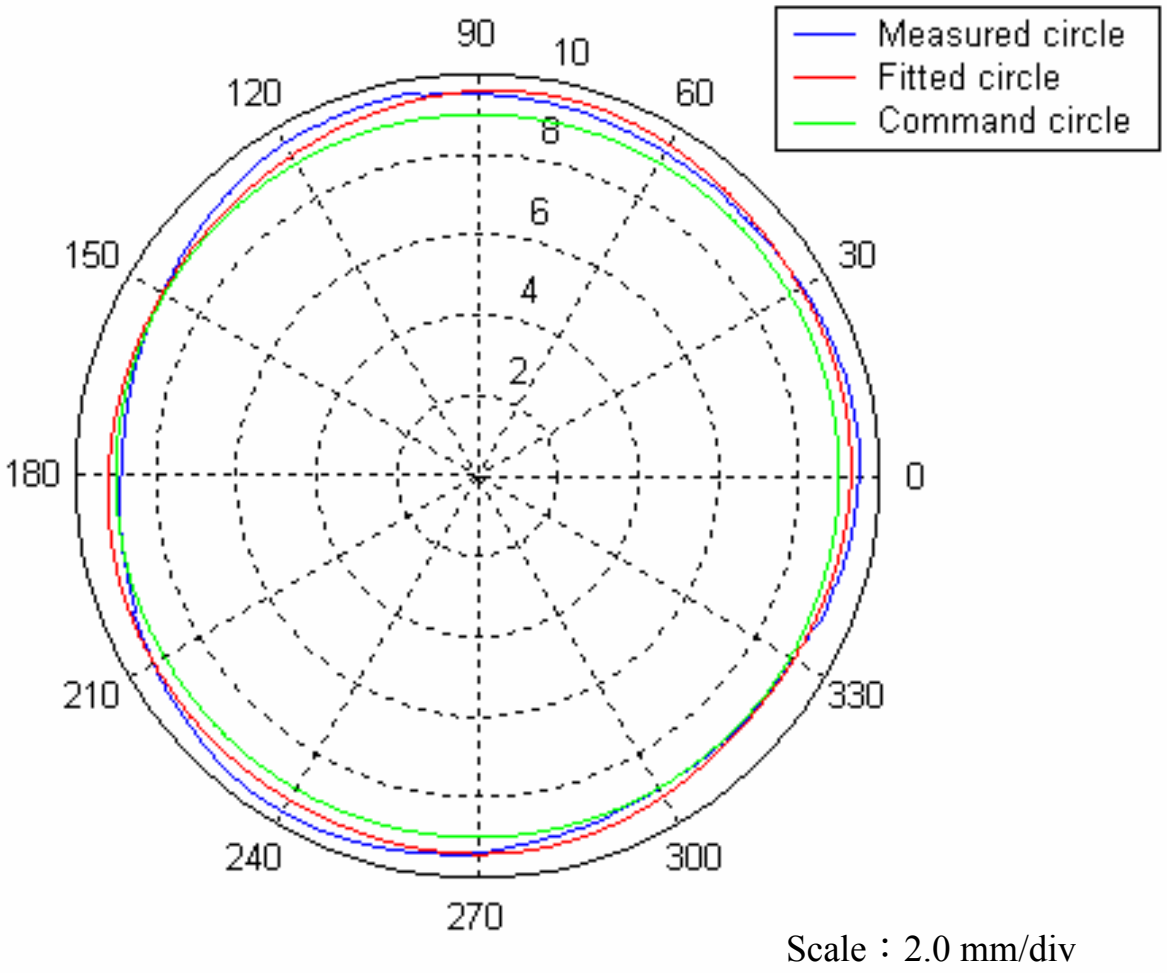


Figure 5.2 Polar plot of error estimation

Position error	Feed motion error	Command generation error
● Geometric error of guide way ・Square error between two axes ・Straightness error of guide way ● Errors of positioning system ・Positioning scale uniform error ・Misalignment between the encoder and motor shaft ・Pitch error of the screw driving system	▪ Error due to servo lag ▪ Mismatch of position loop gain ▪ Lost motion ▪ Stick motion	▪ Interpolation resolution is too rough ▪ Acceleration/Deceleration time constant is too long

Table 1.1. Resources of motiom errors

Item	Error Source	Type	Parameter Error
1	Linkage Length Error	L1	δ_{L1}
2	Linkage Length Error	L2	δ_{L2}
3	Linkage Length Error	L3	δ_{L3}
4	Linkage Length Error	L4	δ_{L4}
5	Linkage Length Error	L5	δ_{L5}
6	Linkage Length Error	L6	δ_{L6}
7	Slider Error	S1	δ_{S1}
8	Slider Error	S2	δ_{S2}
9	Slider Error	S3	δ_{S3}
10	Slider Error	S4	δ_{S4}
11	Slider Error	S5	δ_{S5}
12	Slider Error	S6	δ_{S6}
13	Translation Error_X axis	B1B2	$\delta_{x,b1b2}$
14	Translation Error _Y axis	B1B2	$\delta_{y,b1b2}$
15	Translation Error _X axis	B2B3	$\delta_{x,b2b3}$
16	Translation Error _Y axis	B2B3	$\delta_{y,b2b3}$
17	Translation Error _X axis	B3B1	$\delta_{x,b3b1}$
18	Translation Error _Y axis	B3B1	$\delta_{y,b3b1}$
19	Rotation Error _XY plane	B1B2	$\varepsilon_{xy,b1b2}$
20	Rotation Error_XY plane	B2B3	$\varepsilon_{xy,b2b3}$
21	Rotation Error _XY plane	B3B1	$\varepsilon_{xy,b3b1}$
22	Rotation Error _YZ plane	B1B2	$\varepsilon_{yz,b1b2}$
23	Rotation Error _YZ plane	B2B3	$\varepsilon_{yz,b2b3}$
24	Rotation Error _YZ plane	B3B1	$\varepsilon_{yz,b3b1}$
25	Rotation Error _ about O	B1B2	$\varepsilon_{o,b1b2}$
26	Rotation Error _about O	B2B3	$\varepsilon_{o,b2b3}$
27	Rotation Error _about O	B3B1	$\varepsilon_{o,b3b1}$

Table 3.1 Parameter errors corresponding to geometric errors for a hexglider manipulator

Error	Type	Characteristic equation of geometric error
Tran-_Error X axis	Guideway Type I	$F_1(\theta,\delta)= f^2+g^2+q^2+r^2-b^2- fg-\sqrt{3}grSin\theta-\sqrt{3}fqSin\delta+qrSin\theta Sin\delta-2qrCos\theta Cos\delta + \lambda_{XI}(\sqrt{3}g-qSin\delta-2rSin\theta)=0$
Tran-_Error X axis	Type II	$F_2(\theta,\delta)= f^2+g^2+q^2+r^2-b^2- fg-\sqrt{3}grSin\theta-\sqrt{3}fqSin\delta+qrSin\theta Sin\delta-2qrCos\theta Cos\delta + \lambda_{XII}(\sqrt{3}f-rSin\theta-2qSin\delta)=0$
Tran-_Error Y axis	Type I	$F_3(\theta,\delta)= f^2+g^2+q^2+r^2-b^2- fg-\sqrt{3}grSin\theta-\sqrt{3}fqSin\delta+qrSin\theta Sin\delta-2qrCos\theta Cos\delta + \lambda_{YI}(g-2f+\sqrt{3}qSin\delta)=0$
Tran-_Error Y axis	Type II	$F_4(\theta,\delta)= f^2+g^2+q^2+r^2-b^2- fg-\sqrt{3}grSin\theta-\sqrt{3}fqSin\delta+qrSin\theta Sin\delta-2qrCos\theta Cos\delta + \lambda_{YII}(f-2g+\sqrt{3}rSin\theta)=0$
Tran-_Error Z axis	Type I	$F_5(\theta,\delta)= f^2+g^2+q^2+r^2-b^2- fg-\sqrt{3}grSin\theta-\sqrt{3}fqSin\delta+qrSin\theta Sin\delta-2qrCos\theta Cos\delta + 2\lambda_{ZI}(rCos\theta-qCos\delta)=0$
Tran-_Error Z axis	Type II	$F_6(\theta,\delta)= f^2+g^2+q^2+r^2-b^2- fg-\sqrt{3}grSin\theta-\sqrt{3}fqSin\delta+qrSin\theta Sin\delta-2qrCos\theta Cos\delta - 2\lambda_{ZII}(rCos\theta-qCos\delta)=0$
Rot-_Error XY Plane	Type I	$F_7(\theta,\delta)= f^2+g^2+q^2+r^2-b^2- fg-\sqrt{3}grSin\theta-\sqrt{3}fqSin\delta+qrSin\theta Sin\delta-2qrCos\theta Cos\delta + \varepsilon_{XYI}[-\sqrt{3}fg-3\cdot BR\cdot g+(2\sqrt{3}\cdot BR+g)rSin\theta+(\sqrt{3}\cdot BR+f)qSin\delta+\sqrt{3}qrSin\theta sin\delta]=0$
Rot-_Error XY Plane	Type II	$F_8(\theta,\delta)= f^2+g^2+q^2+r^2-b^2- fg-\sqrt{3}grSin\theta-\sqrt{3}fqSin\delta+qrSin\theta Sin\delta-2qrCos\theta Cos\delta + \varepsilon_{XYII}[\sqrt{3}fg-3\cdot BR\cdot f+(\sqrt{3}\cdot BR-g)rSin\theta+(2\sqrt{3}\cdot BR-f)qSin\delta-\sqrt{3}qrSin\theta sin\delta]=0$
Rot-_Error YZ Plane	Type I	$F_9(\theta,\delta)= f^2+g^2+q^2+r^2-b^2- fg-\sqrt{3}grSin\theta-\sqrt{3}fqSin\delta+qrSin\theta Sin\delta-2qrCos\theta Cos\delta + \varepsilon_{YZI}[-\sqrt{3}fg+grSin\theta+fqSin\delta+2\sqrt{3}\cdot BR\cdot(r-q)Cos\delta+\sqrt{3}qrSin\theta Sin\delta]=0$
Rot-_Error YZ Plane	Type II	$F_{10}(\theta,\delta)= f^2+g^2+q^2+r^2-b^2- fg-\sqrt{3}grSin\theta-\sqrt{3}fqSin\delta+qrSin\theta Sin\delta-2qrCos\theta Cos\delta + \varepsilon_{YZII}[2(\sqrt{3}\cdot BR-g)rCos\theta+(f+2\sqrt{3}\cdot BR)qCos\delta+\sqrt{3}qrSin\theta Sin\delta]=0$
Rot-_Error O	Type I	$F_{11}(\theta,\delta)= f^2+g^2+q^2+r^2-b^2- fg-\sqrt{3}grSin\theta-\sqrt{3}fqSin\delta+qrSin\theta Sin\delta-2qrCos\theta Cos\delta + \varepsilon_{OI}[\sqrt{3}fg-2\cdot BR\cdot(f+g)+(2\sqrt{3}\cdot BR-g)rSin\theta+(2\sqrt{3}\cdot BR-f)qSin\delta-\sqrt{3}qrSin\theta Sin\delta]=0$
Rot- Error O	Type II	$F_{12}(\theta,\delta)= f^2+g^2+q^2+r^2-b^2- fg-\sqrt{3}grSin\theta-\sqrt{3}fqSin\delta+qrSin\theta Sin\delta-2qrCos\theta Cos\delta - \varepsilon_{OII}[\sqrt{3}fg-2\cdot BR\cdot(f+g)+(2\sqrt{3}\cdot BR-g)rSin\theta+(2\sqrt{3}\cdot BR-f)qSin\delta-\sqrt{3}qrSin\theta Sin\delta]=0$

(Remark : Tran- Error→Translation Error, Rot- Error→Rotation Error)

Table 3.2 Characteristic equations of geometric errors for RSSR mechanism

Guide way / Error equation / Error	B1B2	B2B3	B3B1
Shift_Error X Axis	$\begin{cases} F_1(\theta,\delta,f_1,g_1,r_1,r_2)=0 \\ F^*(\delta,\phi,f_2,g_2,r_2,r_3)=0 \\ F_2(\phi,\delta,f_3,g_3,r_3,r_1)=0 \end{cases}$	$\begin{cases} F_2(\theta,\delta,f_1,g_1,r_1,r_2)=0 \\ F_1(\delta,\phi,f_2,g_2,r_2,r_3)=0 \\ F^*(\phi,\delta,f_3,g_3,r_3,r_1)=0 \end{cases}$	$\begin{cases} F^*(\theta,\delta,f_1,g_1,r_1,r_2)=0 \\ F_2(\delta,\phi,f_2,g_2,r_2,r_3)=0 \\ F_1(\phi,\delta,f_3,g_3,r_3,r_1)=0 \end{cases}$
Shift_Error Y Axis	$\begin{cases} F_3(\theta,\delta,f_1,g_1,r_1,r_2)=0 \\ F^*(\delta,\phi,f_2,g_2,r_2,r_3)=0 \\ F_4(\phi,\delta,f_3,g_3,r_3,r_1)=0 \end{cases}$	$\begin{cases} F_4(\theta,\delta,f_1,g_1,r_1,r_2)=0 \\ F_3(\delta,\phi,f_2,g_2,r_2,r_3)=0 \\ F^*(\phi,\delta,f_3,g_3,r_3,r_1)=0 \end{cases}$	$\begin{cases} F^*(\theta,\delta,f_1,g_1,r_1,r_2)=0 \\ F_4(\delta,\phi,f_2,g_2,r_2,r_3)=0 \\ F_3(\phi,\delta,f_3,g_3,r_3,r_1)=0 \end{cases}$
Shift_Error Z Axis	$\begin{cases} F_5(\theta,\delta,f_1,g_1,r_1,r_2)=0 \\ F^*(\delta,\phi,f_2,g_2,r_2,r_3)=0 \\ F_6(\phi,\delta,f_3,g_3,r_3,r_1)=0 \end{cases}$	$\begin{cases} F_6(\theta,\delta,f_1,g_1,r_1,r_2)=0 \\ F_5(\delta,\phi,f_2,g_2,r_2,r_3)=0 \\ F^*(\phi,\delta,f_3,g_3,r_3,r_1)=0 \end{cases}$	$\begin{cases} F^*(\theta,\delta,f_1,g_1,r_1,r_2)=0 \\ F_6(\delta,\phi,f_2,g_2,r_2,r_3)=0 \\ F_5(\phi,\delta,f_3,g_3,r_3,r_1)=0 \end{cases}$
Rot_Error XY Plane	$\begin{cases} F_7(\theta,\delta,f_1,g_1,r_1,r_2)=0 \\ F^*(\delta,\phi,f_2,g_2,r_2,r_3)=0 \\ F_8(\phi,\delta,f_3,g_3,r_3,r_1)=0 \end{cases}$	$\begin{cases} F_8(\theta,\delta,f_1,g_1,r_1,r_2)=0 \\ F_7(\delta,\phi,f_2,g_2,r_2,r_3)=0 \\ F^*(\phi,\delta,f_3,g_3,r_3,r_1)=0 \end{cases}$	$\begin{cases} F^*(\theta,\delta,f_1,g_1,r_1,r_2)=0 \\ F_8(\delta,\phi,f_2,g_2,r_2,r_3)=0 \\ F_7(\phi,\delta,f_3,g_3,r_3,r_1)=0 \end{cases}$
Rot_Error YZ Plane	$\begin{cases} F_9(\theta,\delta,f_1,g_1,r_1,r_2)=0 \\ F^*(\delta,\phi,f_2,g_2,r_2,r_3)=0 \\ F_{10}(\phi,\delta,f_3,g_3,r_3,r_1)=0 \end{cases}$	$\begin{cases} F_{10}(\theta,\delta,f_1,g_1,r_1,r_2)=0 \\ F_9(\delta,\phi,f_2,g_2,r_2,r_3)=0 \\ F^*(\phi,\delta,f_3,g_3,r_3,r_1)=0 \end{cases}$	$\begin{cases} F^*(\theta,\delta,f_1,g_1,r_1,r_2)=0 \\ F_{10}(\delta,\phi,f_2,g_2,r_2,r_3)=0 \\ F_9(\phi,\delta,f_3,g_3,r_3,r_1)=0 \end{cases}$
Rot_Error O	$\begin{cases} F_{11}(\theta,\delta,f_1,g_1,r_1,r_2)=0 \\ F^*(\delta,\phi,f_2,g_2,r_2,r_3)=0 \\ F_{12}(\phi,\delta,f_3,g_3,r_3,r_1)=0 \end{cases}$	$\begin{cases} F_{12}(\theta,\delta,f_1,g_1,r_1,r_2)=0 \\ F_{11}(\delta,\phi,f_2,g_2,r_2,r_3)=0 \\ F^*(\phi,\delta,f_3,g_3,r_3,r_1)=0 \end{cases}$	$\begin{cases} F^*(\theta,\delta,f_1,g_1,r_1,r_2)=0 \\ F_{12}(\delta,\phi,f_2,g_2,r_2,r_3)=0 \\ F_{11}(\phi,\delta,f_3,g_3,r_3,r_1)=0 \end{cases}$

Table 3.3 Systems of error equations for hexglider manipulator

Parameter error / Error source	Given Error Value	Estimated Error Value
LLError_L1_B1B2	0.02mm	0.019996 mm
LLError_L3_B2B3	0.03mm	0.030002 mm
LLError_L5_B2B3	-0.02mm	-0.019994 mm
ShiftError_X_B1B2	-0.01mm	-0.010001mm
ShiftError_X_B2B3	-0.04mm	-0.040019mm

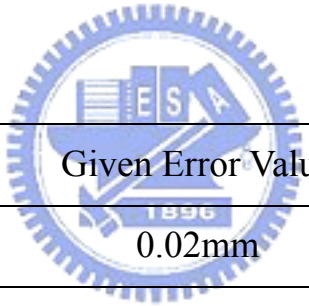
Table 5.1 Error estimation with given errors (1)

Parameter error / Error source	Given Error Value	Estimated Error Value
LLError_L1_B1B2	0.02mm	0.019996 mm
LLError_L3_B2B3	0.03mm	0.030002 mm
LLError_L5_B2B3	-0.02mm	-0.019994 mm
ShiftError_X_B1B2	-0.01mm	-0.014276mm
ShiftError_Y_B1B2	0.02mm	0.012598mm
ShiftError_X_B2B3	-0.04mm	-0.040019mm

Table 5.2 Error estimation with given errors (2)

Parameter error / Error source	Given Error Value	Estimated Error Value
LLError_L1_B1B2	0.02mm	0.04747 mm
LLError_L2_B2B3	-0.01mm	0.01746 mm
LLError_L3_B2B3	0.03mm	0.02999 mm
LLError_L5_B2B3	-0.02mm	-0.01999 mm

Table 5.3 Error estimation with given errors (3)



Parameter error / Error source	Given Error Value	Estimated Error Value
LLError_L1_B1B2	0.02mm	0.02001 mm
LLError_L3_B2B3	0.03mm	0.02999 mm
LLError_L5_B2B3	-0.02mm	-0.02000 mm
ShiftError_X_B1B2	-0.01mm	-0.01002mm
ShiftError_X_B2B3	-0.04mm	-0.04002mm
Rot_XY_B1B2	0.01deg	0.00999deg

Table 5.4 Error estimation with given errors (4)

Parameter error / Error source	Given Error Value	Estimated Error Value
LLError_L1_B1B2	0.02mm	0.01999 mm
LLError_L3_B2B3	0.03mm	0.03035 mm
LLError_L5_B2B3	-0.02mm	-0.02048 mm
ShiftError_X_B1B2	-0.01mm	-0.00915mm
ShiftError_X_B2B3	-0.04mm	-0.03847mm
Rot_XY_B1B2	0.01deg	0.01003deg
Rot_YZ_B2B3	0.02deg	0.01994deg

Table 5.5 Error estimation with datum based on DBB test (5)

Parameter error / Error source	Given Error Value	Estimated Error Value
LLError_L1_B1B2	0.02mm	0.01987mm
LLError_L3_B2B3	0.03mm	0.02981mm
LLError_L5_B2B3	-0.02mm	-0.02008mm
ShiftError_X_B1B2	-0.01mm	-0.0527mm
ShiftError_X_B2B3	-0.04mm	-0.02777mm
Rot_XY_B1B2	0.01deg	0.01038deg
Rot_XY_B2B3	-0.02deg	-0.01950deg
Rot_YZ_B2B3	0.02deg	0.01965deg

Table 5.6 Error estimation with given errors (6)

Parameter error / Error source	Given Error Value	Estimated Error Value
LLError_L1_B1B2	0.02mm	0.01966mm
LLError_L3_B2B3	0.03mm	0.02918mm
LLError_L5_B2B3	-0.02mm	-0.02008mm
ShiftError_X_B1B2	-0.01mm	0.01289mm
ShiftError_X_B2B3	-0.04mm	0.01233mm
Rot_XY_B1B2	0.01deg	0.01104deg
Rot_XY_B2B3	-0.02deg	-0.01831deg
Rot_YZ_B1B2	-0.03deg	-0.02931deg
Rot_YZ_B2B3	0.02deg	0.01862deg

Table 5.7 Error estimation with given errors (7)

Error source	Estimated Error Value
LLError_L1_B1B2	-1.419mm
LLError_L3_B2B3	4.479mm
LLError_L5_B2B3	-5.091mm
ShiftError_X_B1B2	2.509mm
ShiftError_X_B2B3	8.046mm
Rot_XY_B1B2	0.141deg
Rot_YZ_B2B3	-0.780deg

Table 5.8 Error estimation with data based on DBB test for the manipulator SP-120