Control Theory and Applications

μ Robust Control: Design Example

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Contents

Reference

Proceedings of the 37th IEEE Conference on Decision & Control
Tampa, Florida USA • December 1998

Application of μ-Analysis and Synthesis to Follow-up Control of a Profile Measuring System

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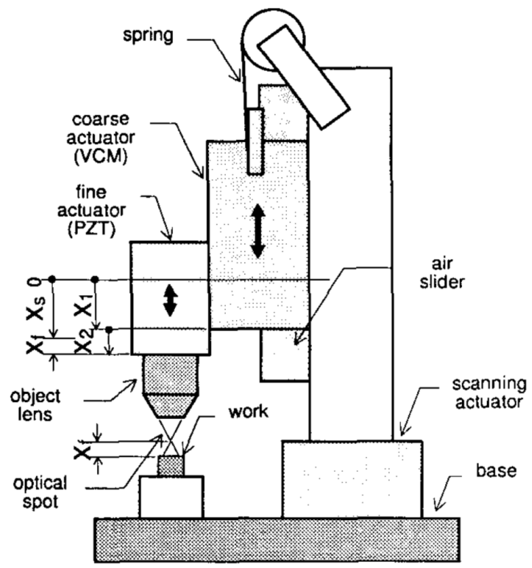
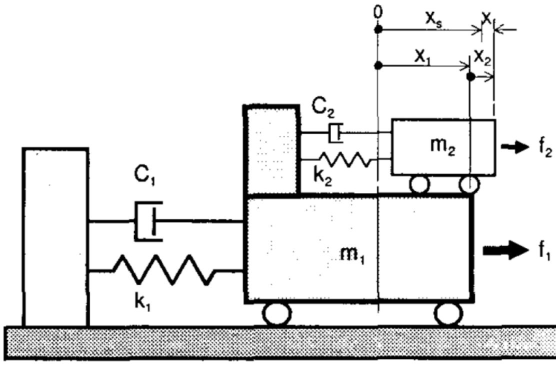
M. Takahashi, M. Kamoshita and M. Fujita,
"Application of μ-Analysis and Synthesis to Follow-up Control of a Profile Measuring System, "
in *Proc. of the 37th IEEE Conference on Decision and Control*,
pp. 4742-4747, 1998.

Profile Measuring System

Real Physical System



Ideal Physical Model



f_1 : the force of coarse actuator

m_1 : the mass of coarse actuator

k_1 : the spring constant of coarse actuator

C_1 : the damping coefficient of coarse actuator

f_2 : the force of fine actuator

m_2 : the mass of fine actuator

k_2 : the spring constant of fine actuator

C_2 : the damping coefficient of fine actuator

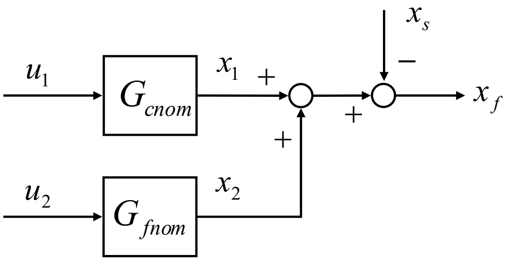
Configuration of coarse actuator and fine actuator

Ideal Mathematical Model

$$m_1 \frac{d^2 x_1}{dt^2} + C_1 \frac{dx_1}{dt} + k_1 x_1 = f_1, \quad m_2 \frac{d^2 x_2}{dt^2} + C_2 \frac{dx_2}{dt} + k_2 x_2 = f_2 \qquad (1)$$

$$f_1 = K_{f1} u_1, \quad f_2 = K_{f2} u_2 \qquad (2)$$

$$x_f = x_1 + x_2 - x_s \qquad (3)$$



Block diagram of Profile measuring system

Nominal Model

$$G_{cnom} = \frac{x_1}{u_1} = \frac{G_{co\_nom}}{s^2 + (2\zeta_{cnom}\omega_{cnom} + K_v)s + \omega_{cnom}^{\;2}} \qquad (4)$$

$$G_{fnom} = \frac{x_2}{u_2} = \frac{G_{fi\_nom1}}{s^2 + 2\zeta_{fnom1}\omega_{fnom1}s + \omega_{fnom1}^{\;2}} + \frac{G_{fi\_nom2}}{s^2 + 2\zeta_{fnom2}\omega_{fnom2}s + \omega_{fnom2}^{\;2}} \qquad (5)$$

$$G_{co\_nom} = 0.5318, \quad \zeta_{cnom} = 0.141, \quad \omega_{cnom} = 5.1321, \quad K_v = 8.9$$

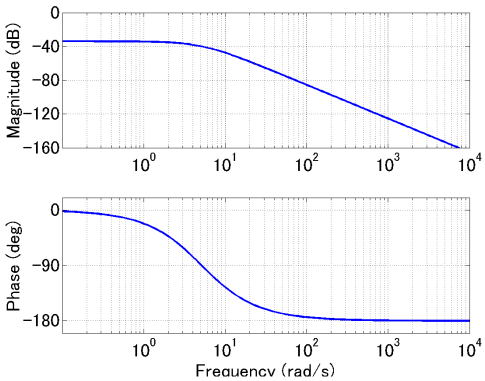
$$G_{fi\_nom1} = 888264, \quad \zeta_{fnom1} = 1, \quad \omega_{fnom1} = 942,$$

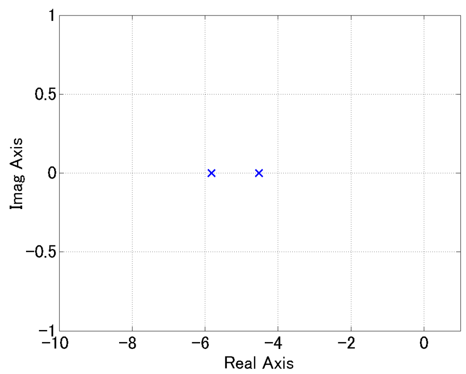
$$G_{fi\_nom2} = 895371, \quad \zeta_{fnom2} = 0.04, \quad \omega_{fnom2} = 5655,$$

Nominal Model

$$G_{cnom}(s) = \frac{0.532}{(s+5.83)(s+4.52)}$$ 2[nd] order LTI system

Poles: $-5.83, \; -4.52$





MATLAB Program

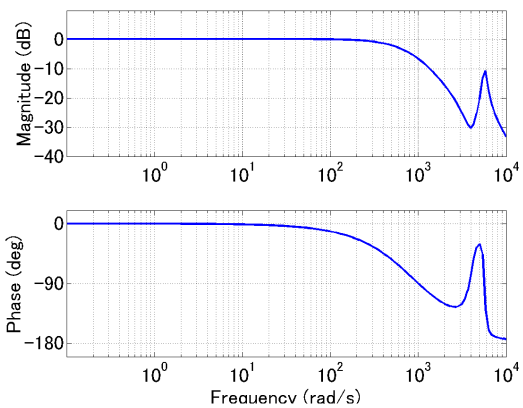
```
% Parameters
Gco_nom=0.5318;
zeta_cnom=0.141;
omega_cnom=5.1321;
Kv=8.9;
% Gcnom
Gcnom_tf=tf([Gco_nom],[1  2*zeta_cnom…
        *omega_cnom+Kv omega_cnom^2]);
Gcnom = nd2sys([Gco_nom],[1 …2*zeta_cnom…
         *omega_cnom+Kv omega_cnom^2]);
zpk(Gcnom_tf)
%
Gcnom_p=frsp(Gcnom,omega1);
Gcnom_g=20*log10(abs(vunpck(Gcnom_p)));
Gcnom_g=vpck(Gcnom_g,omega1);
```

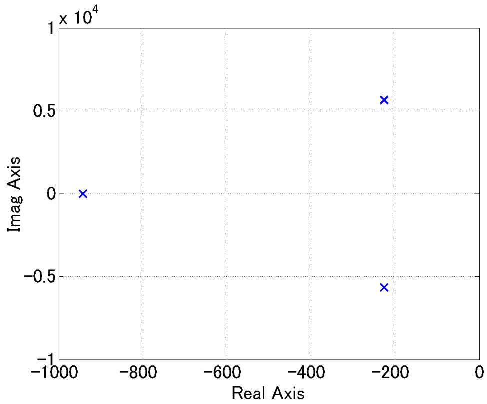
```
%
figure('Position',pos1)
subplot(2,1,1)
vplot('liv,d',Gcnom_g)
subplot(2,1,2)
vplot('liv,p',Gcnom_p)
%
Gcnom_pole=spoles(Gcnom)
Gcnom_zero=szeros(Gcnom)
%
figure('Position',pos2)
vplot('ri', Gcnom_pole,'yx')
```


$$G_{fnom}(s)=\frac{1.78\times10^{6}(s+5.86\times10^{2}\pm j4.00\times10^{3})}{(s+942)^{2}(s+2.26\times10^{2}\pm j5.65\times10^{3})}$$

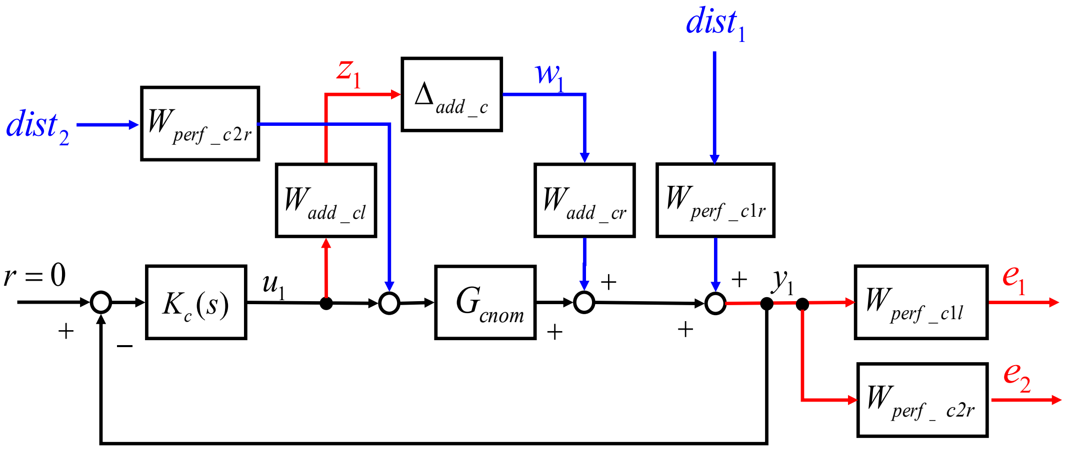
4th-order LTI system

Poles: $-942,\ -2.26\times10^{2}\pm j5.65\times10^{3}$



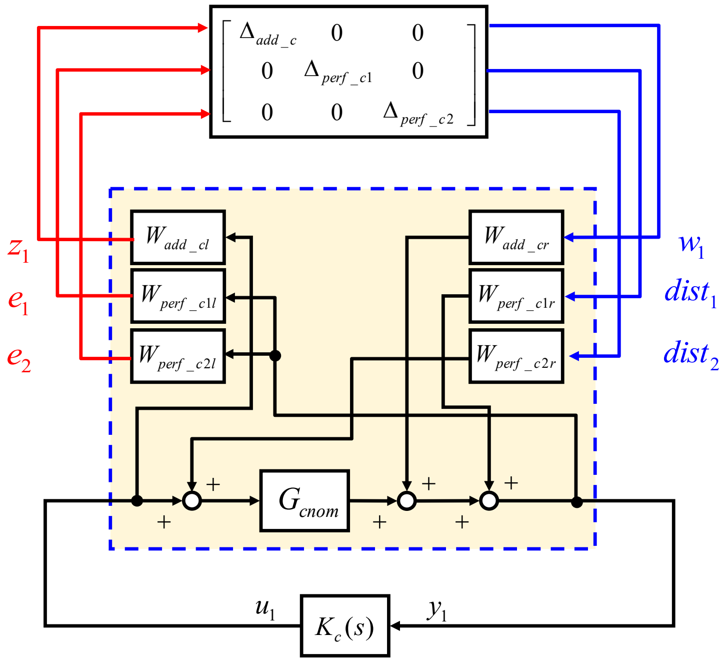


μ Control strategy for first loop



Feedback Structure

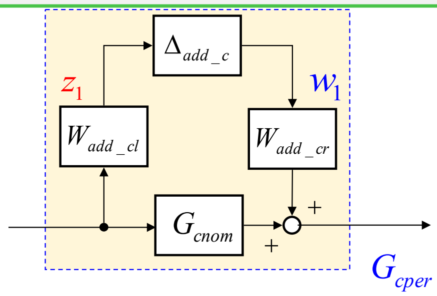
Overall Framework



Generalized Plant of coarse actuator

Perturbed Model

$$G_{cper} = \frac{G_{co}}{s^2 + (2\zeta_c \omega_c + K_v)s + \omega_c^{\,2}}$$



Uncertain 1 $\omega_c = \omega_{cnom} \times (1 \pm 0.1)$

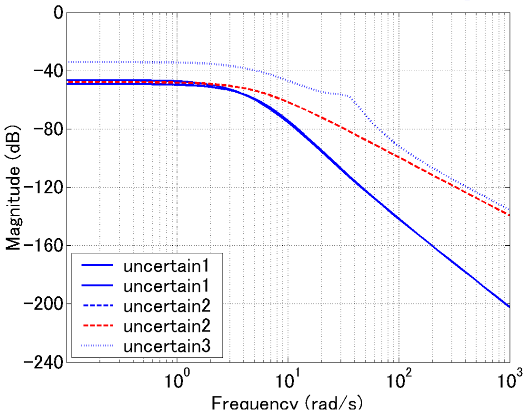
Uncertain 2 $G_{co} = G_{co\_nom} \times (1 \pm 0.2)$

Uncertain 3 (Fine motion)

$$G_{co} = \omega_{co\_nom}' = 0.697$$
$$\zeta_c = \zeta_{cnom}' = 0.073$$
$$\omega_c = \omega_{cnom}' = 35.331$$

$$G_{cper} = G_{cnom} + W_{add\_c}\Delta_{add\_c}$$

$$\Rightarrow \quad |W_{add\_c}| \le |G_{cper} - G_{cnom}|$$



MATLAB Program

```
omega2=logspace(-1,4,50);
% G_cper
Gco = [Gco_nom*0.8 Gco_nom*1.2 0.697];
zeta_c = 0.073;
omega_c = [omega_cnom*0.9 omega_cnom*1.1 35.331];

% uncertain 1  ω_c = ω_cnom × (1 − 0.1)
Gper11 = nd2sys([Gco_nom],[1 2*zeta_cnom*omega_c(1)+Kv omega_c(1)^2]);
Delta11 = msub(Gper11,Gcnom);
Delta11_p=frsp(Delta11,omega2);
Delta11_g=20*log10(abs(vunpck(Delta11_p)));
Delta11=vpck(Delta11_g,omega2);

% uncertain 1  ω_c = ω_cnom × (1 + 0.1)
Gper12 = nd2sys([Gco_nom],[1 2*zeta_cnom*omega_c(2)+Kv omega_c(2)^2]);
Delta12 = msub(Gper12,Gcnom);
Delta12_p=frsp(Delta12,omega2);
Delta12_g=20*log10(abs(vunpck(Delta12_p)));
Delta12=vpck(Delta12_g,omega2);
```

MATLAB Program

```
% uncertain 2   G_co = G_co_nom × (1 − 0.2)
Gper21 = nd2sys([Gco(1)],[1 2*zeta_cnom*omega_cnom+Kv omega_cnom^2]);
Delta21 = msub(Gper21,Gcnom);
Delta21_p=frsp(Delta21,omega2);
Delta21_g=20*log10(abs(vunpck(Delta21_p)));
Delta21=vpck(Delta21_g,omega2);
% uncertain 2   G_co = G_co_nom × (1 + 0.2)
Gper22 = nd2sys([Gco(2)],[1 2*zeta_cnom*omega_cnom+Kv omega_cnom^2]);
Delta22 = msub(Gper22,Gcnom);
Delta22_p=frsp(Delta22,omega2);
Delta22_g=20*log10(abs(vunpck(Delta22_p)));
Delta22=vpck(Delta22_g,omega2);
%  uncertain 3
Gper3 = nd2sys([Gco(3)],[1 2*zeta_c*omega_c(3)+Kv omega_c(3)^2]);
Delta3 = msub(Gper3,Gcnom);
Delta3_p=frsp(Delta3,omega2);
Delta3_g=20*log10(abs(vunpck(Delta3_p)));
Delta3=vpck(Delta3_g,omega2);
%  Plot
vplot('liv,d',Delta11,Delta12,Delta21,Delta22,Delta3);
```


Weighting Function

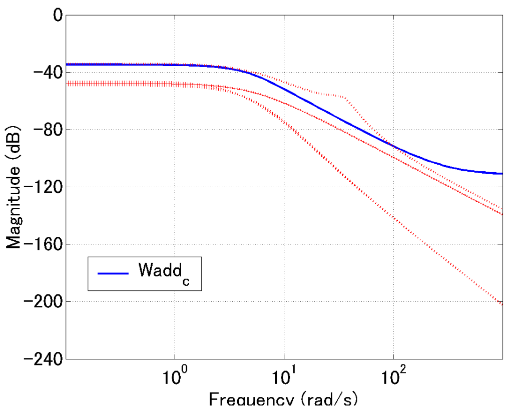
$W_{add\_c}(s)$

$$W_{add\_cl} = 2.634\times10^{-6}\times\frac{s+8}{s+3.9}\times\frac{s^2+600s+90000}{s^2+8.211s+26.339}\times10^{-3}$$

$$W_{add\_cr} = 10^3$$

$$W_{add\_c} = W_{add\_cl}\times W_{add\_cr}$$

$$W_{add\_c} = 2.634\times10^{-6}\times\frac{s+8}{s+3.9}\times\frac{s^2+600s+90000}{s^2+8.211s+26.339}$$



Weighting Function

MATLAB Program

```
Wadd_cl_1 = nd2sys([1 6e2 9e4],…
                   [1 8.211 26.339],1e-3);
Wadd_cl_2 = nd2sys([1 8], [1 3.9],2.634e-6);
Wadd_cl = mmult(Wadd_cl_1,Wadd_cl_2);
% right
Wadd_cr = 1e3;
% Wadd
Wadd_c = mmult(Wadd_cl,Wadd_cr);
Waddc_p=frsp(Wadd_c,omega1);
Waddc_g=20*log10(abs(vunpck(Waddc_p)));
Waddc_g=vpck(Waddc_g,omega1);

figure('Position',pos1)
vplot('liv,d',Waddc_g,Delta11,Delta12,…
                 Delta21,Delta22,Delta3);
```


Weighting Function

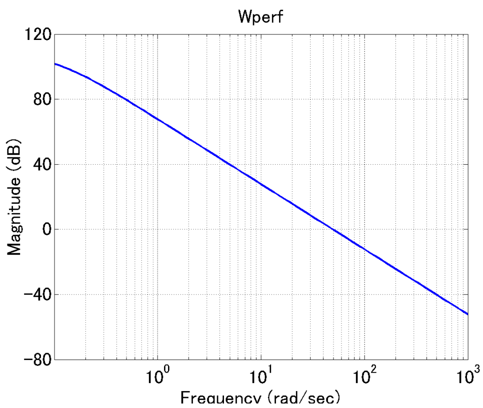
W_{perf_c1}

$$W_{perf\_c1l} = \frac{1211 \times 2}{s^2 + 0.2s + 0.1^2} \times 10^{-3}$$

$$W_{perf\_c1r} = 10^3$$

$$W_{perf\_c1} = W_{perf\_c1l} \times W_{perf\_c1r}$$

$$W_{perf\_c1} = \frac{1211 \times 2}{s^2 + 0.2s + 0.1^2}$$



MATLAB Program

```
Wperf_c1l = nd2sys([1211*2*1e-3],[1 0.2 0.1^2]);
Wperf_c1r = 1e3;

Wperf_c1 = mmult(Wperf_c1l,Wperf_c1r);
Wperf_c1_p=frsp(Wperf_c1,omega1);
Wperf_c1_g=20*log10(abs(vunpck(Wperf_c1_p)));
Wperf_c1_g=vpck(Wperf_c1_g,omega1);

figure('Position',pos1)
vplot('liv,d',Wperf_c1_g)
```

Weighting Function

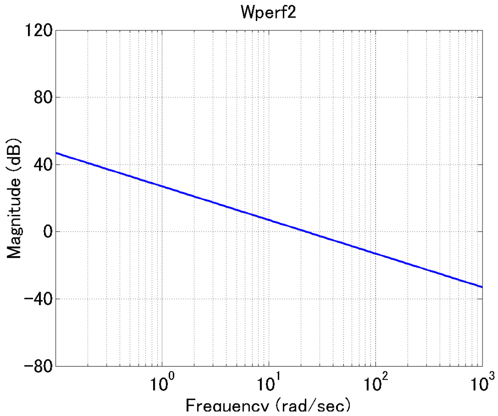
W_{perf_c2}

$$W_{perf\_c2l} = \frac{22}{s+0.01} \times 10^{-3}$$

$$W_{perf\_c2r} = 10^3 \times \frac{1}{G_{co\_nom}}$$

$$W_{perf\_c2} = W_{perf\_c2l} \times W_{perf\_c2r}$$

$$W_{perf\_c2} = \frac{22}{s+0.01}$$



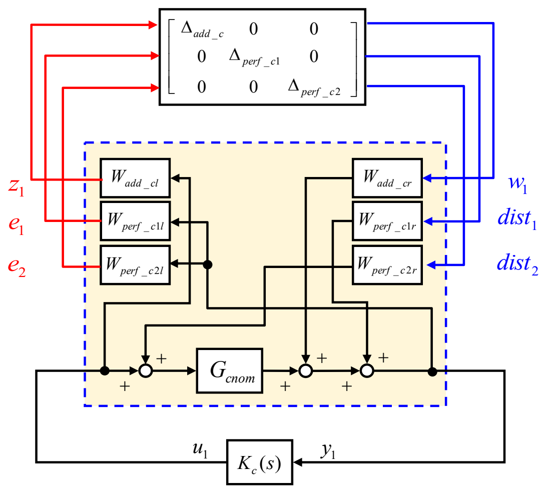
MATLAB Program

```
Wperf_c2l = nd2sys([Gco_nom*22e-3],[1 0.01]);
Wperf_c2r = 1e3/(Gco_nom);

Wperf_c2 = mmult(Wperf_c2l,Wperf_c2r);
Wperf_c2_p=frsp(Wperf_c2,omega1);
Wperf_c2_g=20*log10(abs(vunpck(Wperf_c2_p)));
Wperf_c2_g=vpck(Wperf_c2_g,omega1);

figure('Position',pos2)
vplot('liv,d',Wperf_c2_g)
```


Generalized Plant

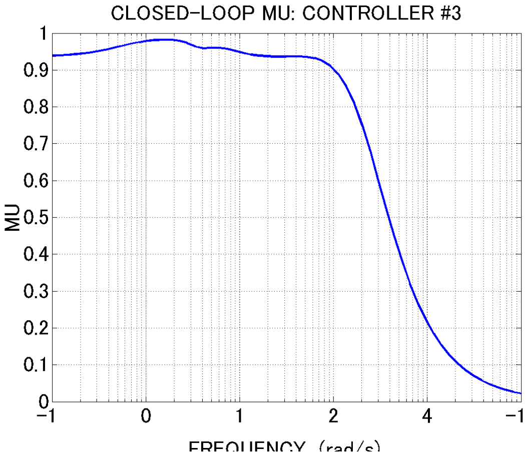
MATLAB Program

```
systemnames = ' Gcnom Wadd_cl Wadd_cr …
  Wperf_c1l Wperf_c1r Wperf_c2l Wperf_c2r ';
inputvar = '[ w1 ; dist1; dist2; control]';
outputvar = '[  Wadd_cl; Wperf_c1l; Wperf_c2l;…
             -Gcnom - Wadd_cr - Wperf_c1r ]';
input_to_Gcnom = '[ Wperf_c2r + control ]';
input_to_Wadd_cl = '[ control ]';
input_to_Wadd_cr = '[ w1 ]';
input_to_Wperf_c1l = '[ Gcnom+Wadd_cr…
                                  +Wperf_c1r ]';
input_to_Wperf_c1r = '[ dist1 ]';
input_to_Wperf_c2l = '[ Gcnom+Wadd_cr…
                                  +Wperf_c1r ]';
input_to_Wperf_c2r = '[ dist2 ]';
sysoutname = 'General_P';
cleanupsysic = 'yes';
sysic
```



D-K Iteration

Iteration Summary			
Iteration #	1	2	3
Controller Order	8	24	28
Total D-Scale Order	0	16	20
Gamma Achieved	1.563	1.166	0.993
Peak mu-Value	1.334	1.110	0.982

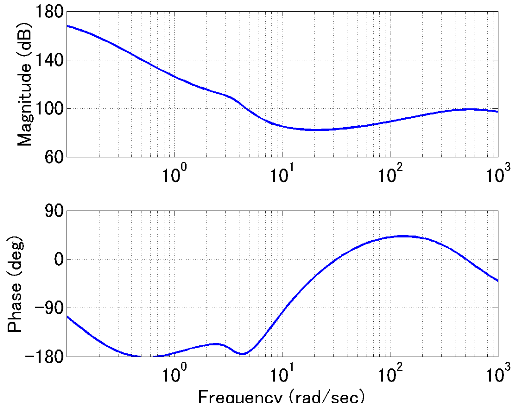


Controller $K_c(s)$

$$K_c(s) = \frac{8.27\times10^{7}(s+0.01)(s+1.13\pm j7.23\times10^{-2})(s+1.81)(s+3.12)}{(s+0.01)(s+0.10\pm j1.13\times10^{-4})(s+0.217)(s+1.60)}$$

$$\times\frac{(s+3.88\pm j3.17)(s+6.91\pm j2.61)(s+3.19\times10)(s+6.68\times10)}{(s+1.62\pm j1.17)(s+1.15\pm j3.33)(s+6.13\times10)}$$

$$\times\frac{(s+4.97\times10^{3})(s+1.63\times10^{4})}{(s+4.63\times10^{2}\pm j3.07\times10^{2})(s+4.99\times10^{3})(s+1.62\times10^{4})}$$



Continue

MATLAB Program himat_dk1.m

```
NOMINAL_DK = General_P;

% Number of measurements
NMEAS_DK = 1;

% Number of control inputs
NCONT_DK = 1;

% Block structure for mu calculation
BLK_DK = [1 1;1 1;1 1];

% Frequency response range
OMEGA_DK = logspace(-1,4,60);

AUTOINFO_DK = [1 3 1]
```


Continue

MATLAB Program

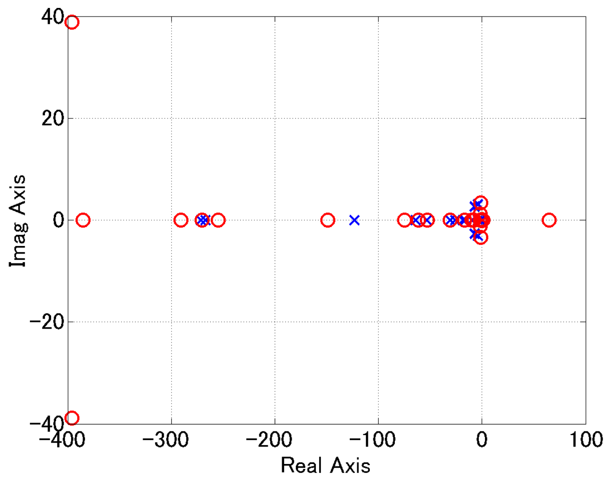
```
[DK_DEF_NAME='himat_dk1';
dkit

k_dk3_p = frsp(k_dk3,omega1);
k_dk3_g = 20*log10(abs(vunpck(k_dk3_p)));
k_dk3_g = vpck(k_dk3_g,omega1);
%
[sysb,sig]=sysbal(k_dk3)
Kc=strunc(sysb,14)

[Kc_a,Kc_b,Kc_c,Kc_d]=unpck(Kc);
[Kc_num,Kc_den]=ss2tf(Kc_a,Kc_b,Kc_c,Kc_d);
Kc_tf=tf(Kc_num,Kc_den);

zpk(Kc_tf)
```

```
Kc_pole=spoles(Kc)
Kc_zero=szeros(Kc)

Kc_p=frsp(Kc,omega1);
Kc_g=20*log10(abs(vunpck(Kc_p)));
Kc_g=vpck(Kc_g,omega1);

figure('Position',pos1)
subplot(2,1,1)
vplot('liv,d',Kc_g)
subplot(2,1,2)
vplot('liv,p',Kc_p)
```

Closed-Loop System

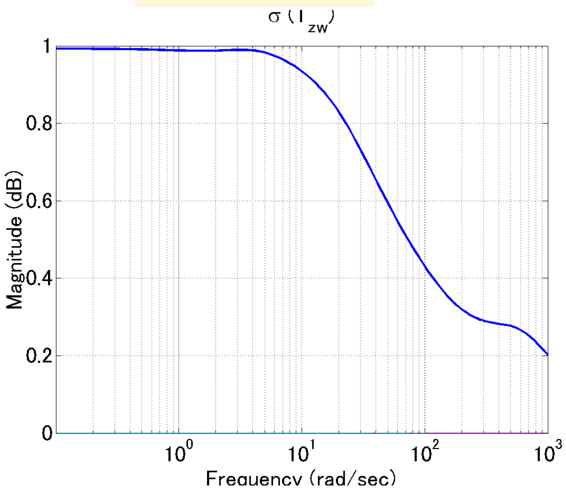
MATLAB Program

```
DGD_c = mmult(dl_dk3,General_P,…
                    minv(dr_dk3));
systemnames = ' Kc DGD_c ';
inputvar = '[ w1 ; dist1; dist2 ]';
outputvar = '[  DGD_c(1); DGD_c(2); …
                    DGD_c(3) ]';
input_to_Kc = '[  -DGD_c(4) ]';
input_to_DGD_c = '[ w1; dist1; dist2; Kc ]';
sysoutname = 'Kc_cloop';
cleanupsysic = 'yes';
Sysic

Kc_close_p=spoles(Kc_cloop)
Kc_close_z=szeros(Kc_cloop)
figure('Position',pos1)
vplot('ri',Kc_close_p,'yx',Kc_close_z,'ro')
```



Continue

$$\sigma_{\max}[\Phi(j\omega)] \leq 1$$



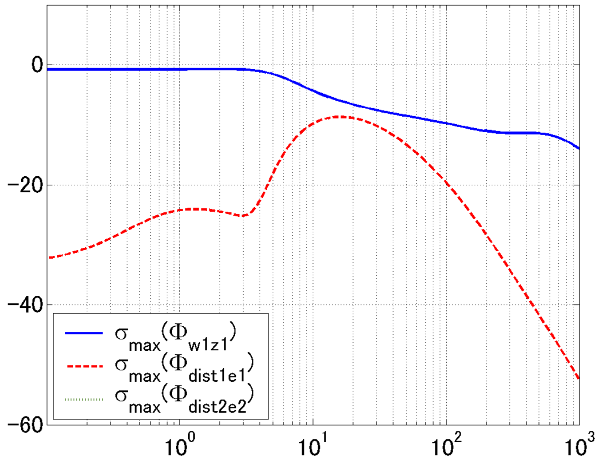
MATLAB Program

```
Kc_cloop_g=frsp(Kc_cloop,omega1);
Kc_cloop_svd_g=vsvd(Kc_cloop_g);

figure('Position',pos2)
vplot('liv,d',Kc_cloop_svd_g)
```

Continue

MATLAB Program

```
nom_perf=sel(Kc_cloop_g,2,2);
nom_perf_g=20*log10(abs…
                    (vunpck(nom_perf)));
nom_perf_g=vpck(nom_perf_g,omega1);

nom_perf2=sel(Kc_cloop_g,3,3);
nom_perf2_g=20*log10(abs…
                    (vunpck(nom_perf2)));
nom_perf2_g=vpck(nom_perf2_g,omega1);

rob_stab=sel(Kc_cloop_g,1,1);
rob_stab_g=20*log10(abs(vunpck(rob_stab)));
rob_stab_g=vpck(rob_stab_g,omega1);

figure('Position',pos3)
vplot('liv,d',rob_stab_g,nom_perf_g,…
                              nom_perf2_g)
```

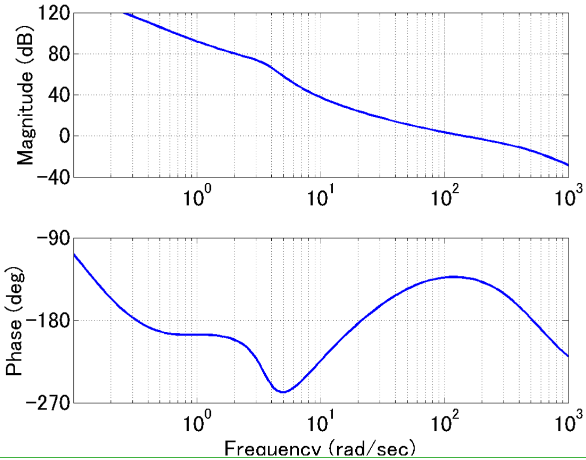


More Continue

MATLAB Program

```
Lc=mmult(Gcnom,Kc);
Lc_p=frsp(Lc,omega1);
Lc_g=20*log10(abs(vunpck(Lc_p)));
Lc_g=vpck(Lc_g,omega1);

[Lc_a,Lc_b,Lc_c,Lc_d]=unpck(Lc);
Lc_ss=ss(Lc_a,Lc_b,Lc_c,Lc_d);
[Lc_Gm,Lc_Pm,Lc_Wcg,Lc_Wcp] =
margin(Lc_ss);

figure('Position',pos1)
subplot(2,1,1)
vplot('liv,d',Lc_g)
subplot(2,1,2)
vplot('liv,p',Lc_p)
```

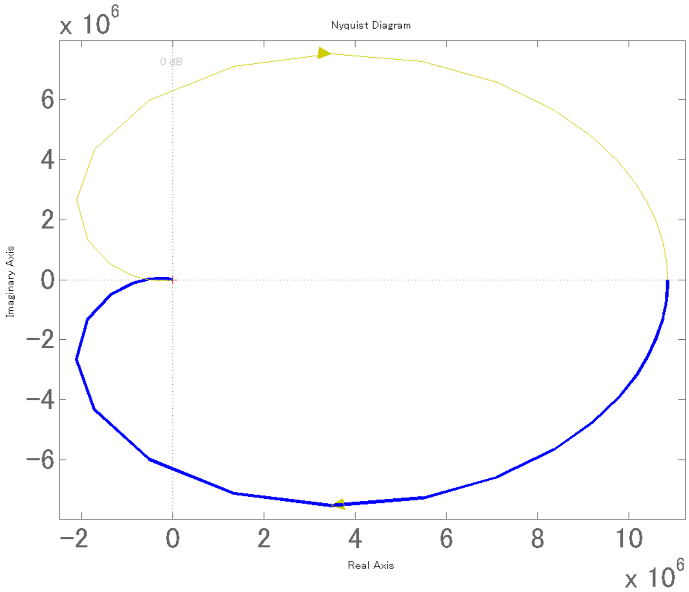
GM	14.9 [dB]
PM	46.5 [deg]



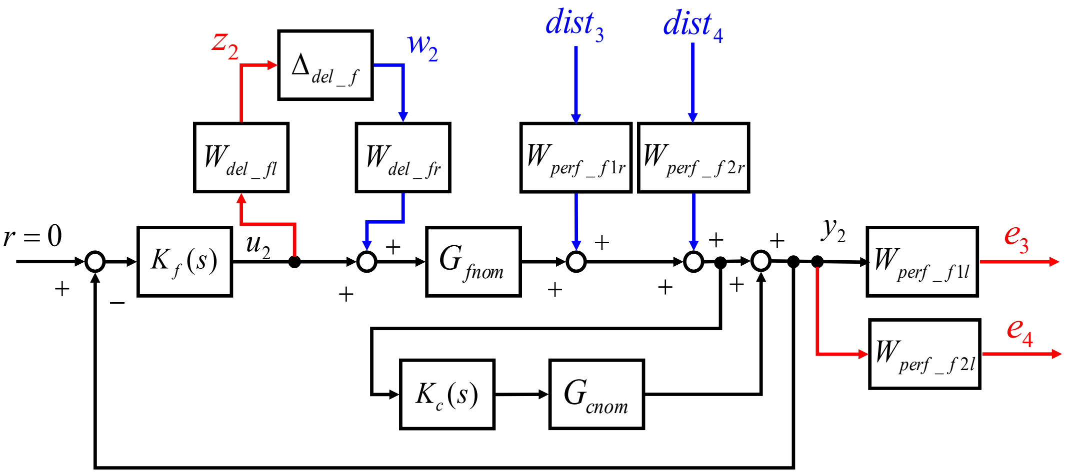
Frequency Response

MATLAB Program

```
figure('Position',pos2)
nyquist(Lc_ss,'y')
```

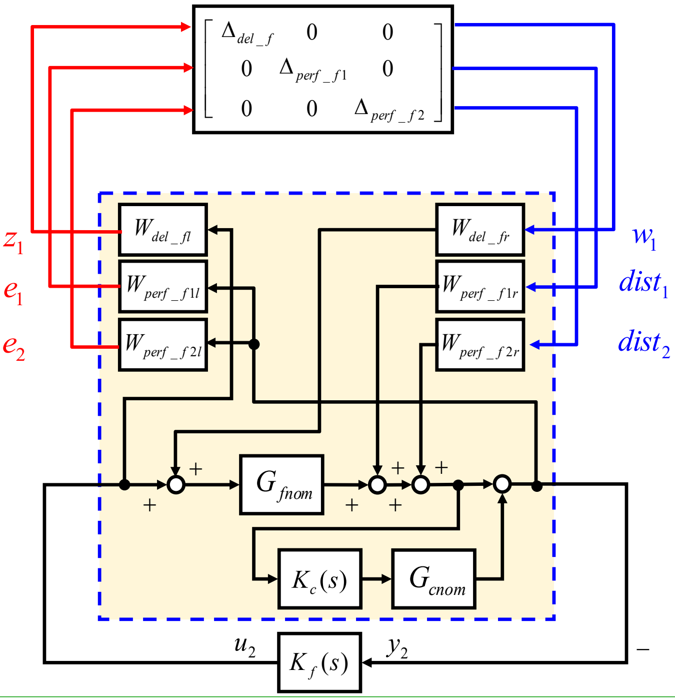


μ Synthesis (2nd Loop)



Feedback Structure

Generalized Plant of Coarse Actuator



Weighting Functions

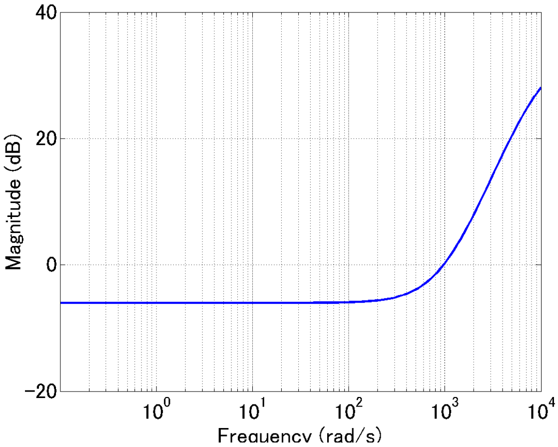
$W_{del\_f}(s)$

$$W_{del\_fl} = 50 \times \frac{(s+800)(s+1200)}{(s+8000)(s+12000)} \times 10^{-2}$$

$$W_{del\_f} = W_{del\_fl} \times W_{del\_fr}$$

$$W_{del\_fr} = 10^2$$

$$W_{del\_f} = 50 \times \frac{(s+800)(s+1200)}{(s+8000)(s+12000)}$$



Weighting Functions

MATLAB Program

```
Wdel_fl = zp2sys([-800; -1200],[-8000; -12000],50e-2);
Wdel_fr = 1e2;
Wdel_f = mmult(Wdel_fl,Wdel_fr);

Wdel_f_p=frsp(Wdel_f,omega1);
Wdel_f_g=20*log10(abs(vunpck(Wdel_f_p)));
Wdel_f_g=vpck(Wdel_f_g,omega1);

figure('Position',pos1)
vplot('liv,d',Wdel_f_g);
```


Weighting Functions

W_{perf_f1}

$$W_{perf\_f1l} = \frac{1211\times 2}{s^2+0.2s+0.1^2}\times 10^{-2}$$

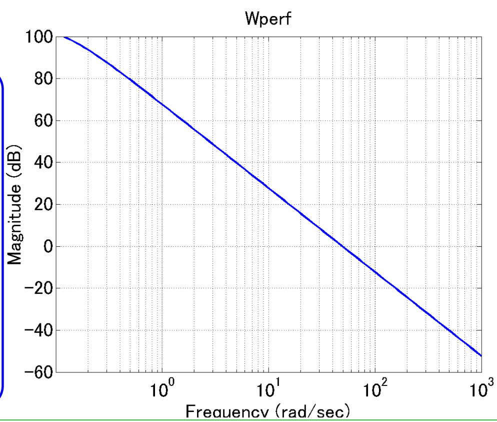
$$W_{perf\_f1r} = 10^2$$

$$W_{perf\_f1} = W_{perf\_f1l}\times W_{perf\_f1r}$$

$$W_{perf\_f1} = \frac{1211\times 2}{s^2+0.2s+0.1^2}$$

MATLAB Program

```
Wperf_f1l = nd2sys([1211*2],[1 0.2 0.1^2],1e-2);
Wperf_f1r = 1e2
Wperf_f1 = mmult(Wperf_f1l,Wperf_f1r);
Wperf_f1_p=frsp(Wperf_f1,omega1);
Wperf_f1_g=20*log10(abs(vunpck(Wperf_f1_p))`
Wperf_f1_g=vpck(Wperf_f1_g,omega1);

figure('Position',pos2)
vplot('liv,d',Wperf_f1_g)
```



Weighting Functions

W_{perf_f2}

$$W_{perf\_f2l} = \frac{360 \times 400}{(s+120)(s+400)} \times 10^{-2}$$

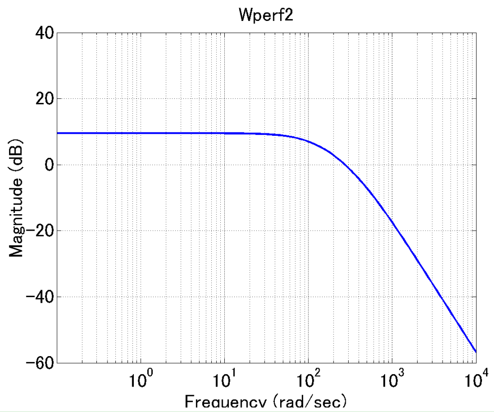
$$W_{perf\_f2r} = 10^{2}$$

$$W_{perf\_f2} = W_{perf\_f2l} \times W_{perf\_f2r}$$

$$W_{perf\_f2} = \frac{360 \times 400}{(s+120)(s+400)}$$

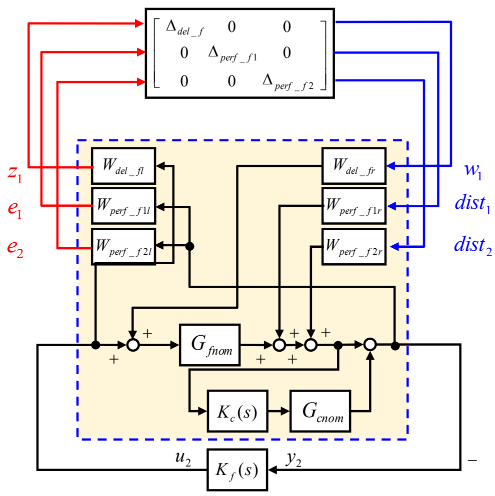
MATLAB Program

```
Wperf_f2l = zp2sys([],[-120; -400],360*400e-2);
Wperf_f2r = 1e2;
Wperf_f2 = mmult(Wperf_f2l,Wperf_f2r);
Wperf_f2_p=frsp(Wperf_f2,omega1);
Wperf_f2_g=20*log10(abs(vunpck(Wperf_f2_p)));
Wperf_f2_g=vpck(Wperf_f2_g,omega1);

figure('Position',pos2)
vplot('liv,d',Wperf_f1_g)
```



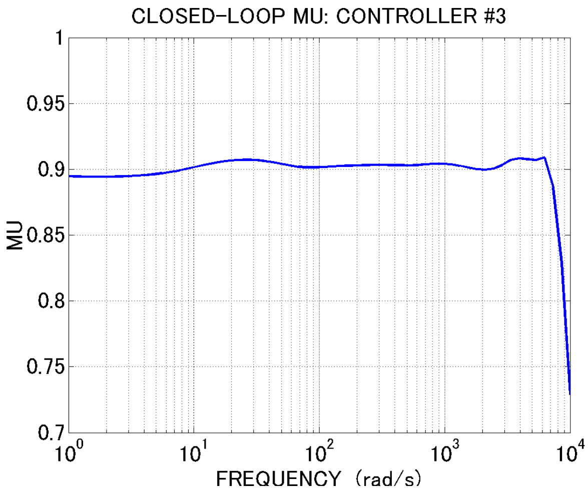
MATLAB Program

```
systemnames = ' Gcnom Kc Gfnom Wdel_fl …
    Wdel_fr Wperf_f1l Wperf_f1r …
    Wperf_f2l Wperf_f2r ';
inputvar = '[ w2 ; dist3; dist4; control]';
outputvar = '[  Wdel_fl; Wperf_f1l; Wperf_f2l; …
      -Gfnom - Wperf_f1r - Wperf_f2r - Gcnom ]';
input_to_Gcnom = '[ Kc ]';
input_to_Kc = '[ Gfnom + Wperf_f1r + Wperf_f2r ]';
input_to_Gfnom = '[ Wdel_fr + control ]';
input_to_Wdel_fl = '[ control ]';
input_to_Wdel_fr = '[ w2 ]';
input_to_Wperf_f1l = '[ Gfnom + Wperf_f1r + Wperf_f2r + Gcnom ]';
input_to_Wperf_f1r = '[ dist3 ]';
input_to_Wperf_c2l = '[ Gfnom + Wperf_f1r + Wperf_f2r + Gcnom ]';
input_to_Wperf_c2r = '[ dist4 ]';
sysoutname = 'General_P2';
cleanupsysic = 'yes';
sysic
```



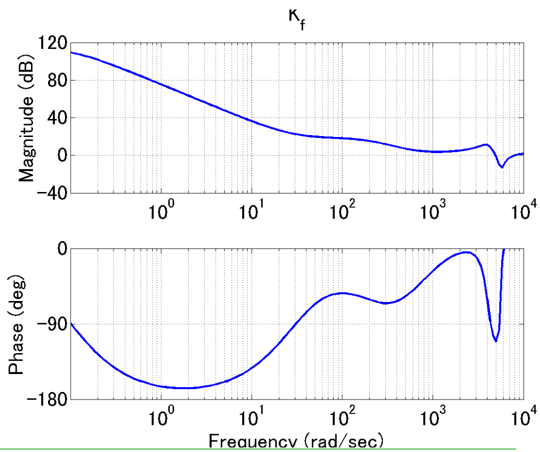
D-K Iteration

Iteration Summary			
Iteration #	1	2	3
Controller Order	26	36	40
Total D-Scale Order	0	10	14
Gamma Achieved	1.909	1.094	0.910
Peak mu-Value	1.826	1.068	0.909



Controller $K_f(s)$

$$K_f(s)=\frac{1.03\times10^4(s+3.64\times10^{-1}\pm j1.21)(s+3.53\times10^{-1}\pm j1.19)(s+1.43)}{(s+3.65\times10^{-1}\pm j1.24)(s+3.07\times10^{-1}\pm j1.17)(s+1.16)(s+1.34)}$$
$$\times\frac{(s+9.32\times10^{-1}\pm j1.96)(s+1.19\pm j1.97)(s+2.27)(s+2.59)(s+3.35)}{(s+1.00\times10^{-1}\pm j1.59\times10^{-5})(s+2.63)(s+2.94\times10^{-1}\pm j2.11\times10)}$$
$$\times\frac{(s+3.50\times10)(s+6.30\times10)(s+2.73\times10\pm j5.06\times10)(s+1.03\times10^2)}{(s+1.49\pm j2.22)(s+1.14\times10)(s+2.22\times10)(s+4.36\times10)(s+1.26\times10^2)}$$
$$\times\frac{(s+4.61\times10^2\pm j3.06\times10^2)(s+9.45\times10^2\pm j2.75\times10)}{(s+2.30\times10^2\pm j8.75\times10)(s+3.78\times10^2)(s+2.07\times10^3\pm j9.69\times10^2)}$$
$$\times\frac{(s+2.26\times10^2\pm j5.65\times10^3)}{(s+6.26\times10^2\pm j4.02\times10^3)}$$
$$\times\frac{(s+8.00\times10^3)(s+1.20\times10^4)}{(s+1.92\times10^4\pm j1.61\times10^4)}$$



Continue

MATLAB Program himat_dk2.m

```
NOMINAL_DK = General_P2;

% Number of measurements
NMEAS_DK = 1;

% Number of control inputs
NCONT_DK = 1;

% Block structure for mu calculation
BLK_DK = [1 1;1 1;1 1];

% Frequency response range
OMEGA_DK = logspace(0,4,60);

AUTOINFO_DK = [1 3 1]
```


Continue

MATLAB Program

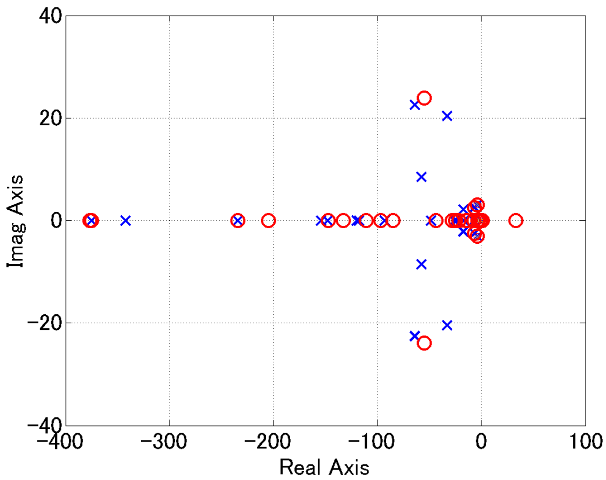
```
DK_DEF_NAME='himat_dk2';
dkit

k_dk3_p = frsp(k_dk3,omega1);
k_dk3_g = 20*log10(abs(vunpck(k_dk3_p)));
k_dk3_g = vpck(k_dk3_g,omega1);
% 低次元化
[sysb,sig]=sysbal(k_dk3)
Kf=strunc(sysb,36)
[Kf_a,Kf_b,Kf_c,Kf_d]=unpck(Kf);
[Kf_num,Kf_den]=ss2tf(Kf_a,Kf_b,Kf_c,Kf_d);
Kf_tf=tf(Kf_num,Kf_den);zpk(Kf_tf)

Kf_pole=spoles(Kf)
Kf_zero=szeros(Kf)
```

```
Kf_p=frsp(Kf,omega1);
Kf_g=20*log10(abs(vunpck(Kf_p)));
Kf_g=vpck(Kf_g,omega1);

figure('Position',pos1)
subplot(2,1,1)
vplot('liv,d',Kf_g)
subplot(2,1,2)
vplot('liv,p',Kf_p)
```

Closed-Loop System

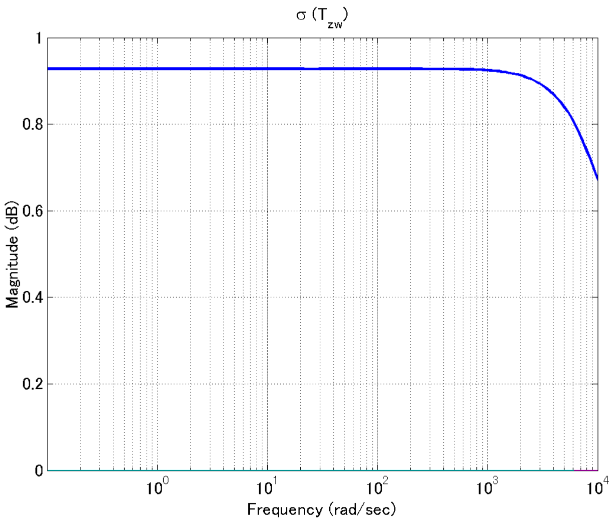
MATLAB Program

```
DGD_f = mmult(dl_dk3,General_P2,…
                    minv(dr_dk3));
systemnames = ' Kf DGD_f ';
inputvar = '[ w2 ; dist3; dist4 ]';
outputvar = '[  DGD_f(1); DGD_f(2); …
                    DGD_f(3) ]';
input_to_Kf = '[  -DGD_f(4) ]';
input_to_DGD_f = '[ w2; dist3; dist4; Kf ]';
sysoutname = 'Kf_cloop';
cleanupsysic = 'yes';
Sysic

Kf_close_p=spoles(Kf_cloop)
Kf_close_z=szeros(Kf_cloop)
figure('Position',pos1)
vplot('ri',Kf_close_p,'yx',Kf_close_z,'ro')
```



Continue

$$\sigma_{\max}[\Phi(j\omega)] \le 1$$



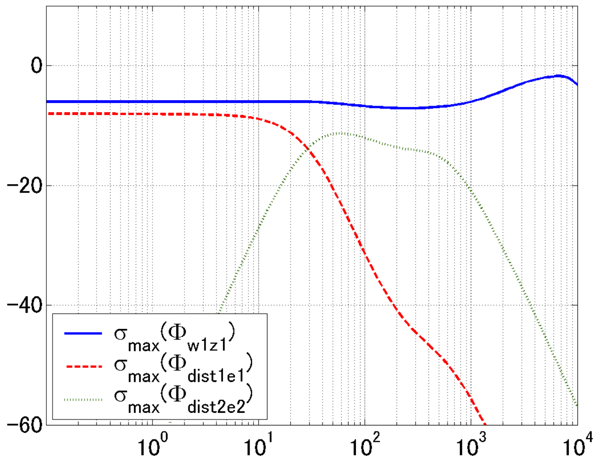
MATLAB Program

```
Kf_cloop_g=frsp(Kf_cloop,omega1);
Kf_cloop_svd_g=vsvd(Kf_cloop_g);

figure('Position',pos2)
vplot('liv,d',Kf_cloop_svd_g)
```

Continue

MATLAB Program

```
nom_perf=sel(Kf_cloop_g,2,2);
nom_perf_g=20*log10(abs…
                    (vunpck(nom_perf)));
nom_perf_g=vpck(nom_perf_g,omega1);

nom_perf2=sel(Kf_cloop_g,3,3);
nom_perf2_g=20*log10(abs…
                    (vunpck(nom_perf2)));
nom_perf2_g=vpck(nom_perf2_g,omega1);

rob_stab=sel(Kf_cloop_g,1,1);
rob_stab_g=20*log10(abs(vunpck(rob_stab)));
rob_stab_g=vpck(rob_stab_g,omega1);

figure('Position',pos3)
vplot('liv,d',rob_stab_g,nom_perf_g,…
                    nom_perf2_g)
```

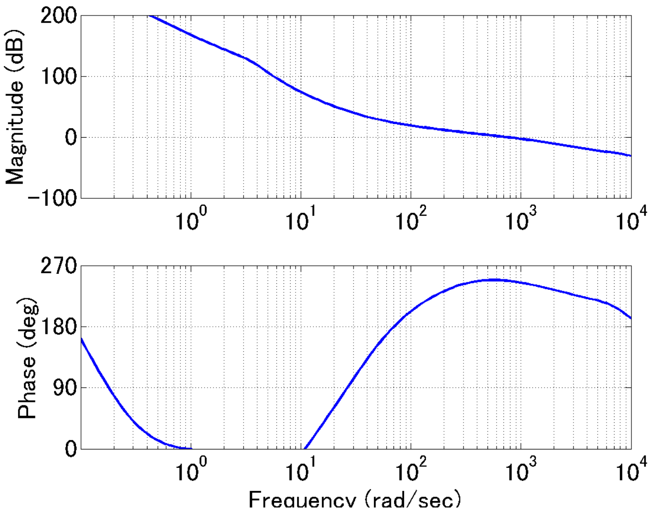


Continue

MATLAB Program

```
Lf=mmult(madd(Gfnom,mmult(Gfnom,Kc
,Gcnom)),Kf);
Lf_p=frsp(Lf,omega1);
Lf_g=20*log10(abs(vunpck(Lf_p)));
Lf_g=vpck(Lf_g,omega1);

[Lc_a,Lc_b,Lc_c,Lc_d]=unpck(Lc);
Lc_ss=ss(Lc_a,Lc_b,Lc_c,Lc_d);
[Lc_Gm,Lc_Pm,Lc_Wcg,Lc_Wcp] =
margin(Lc_ss);

figure('Position',pos1)
subplot(2,1,1)
vplot('liv,d',Lc_g)
subplot(2,1,2)
vplot('liv,p',Lc_p)
```

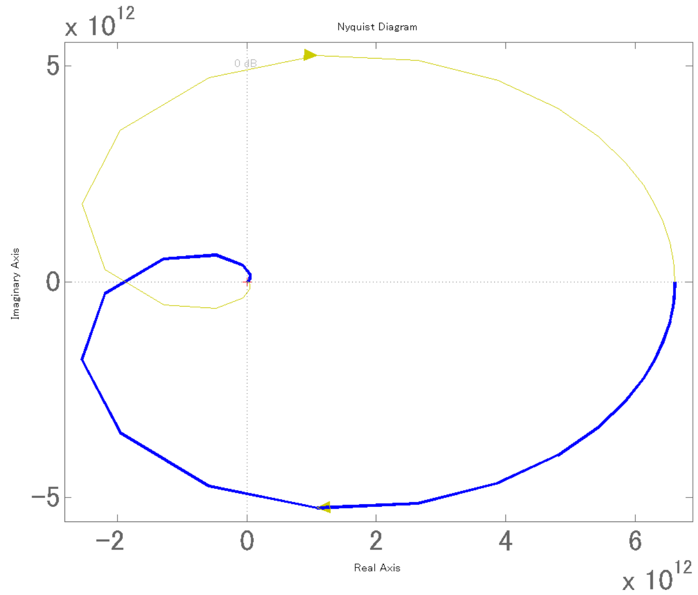
GM	23.7 [dB]
PM	67.6 [deg]



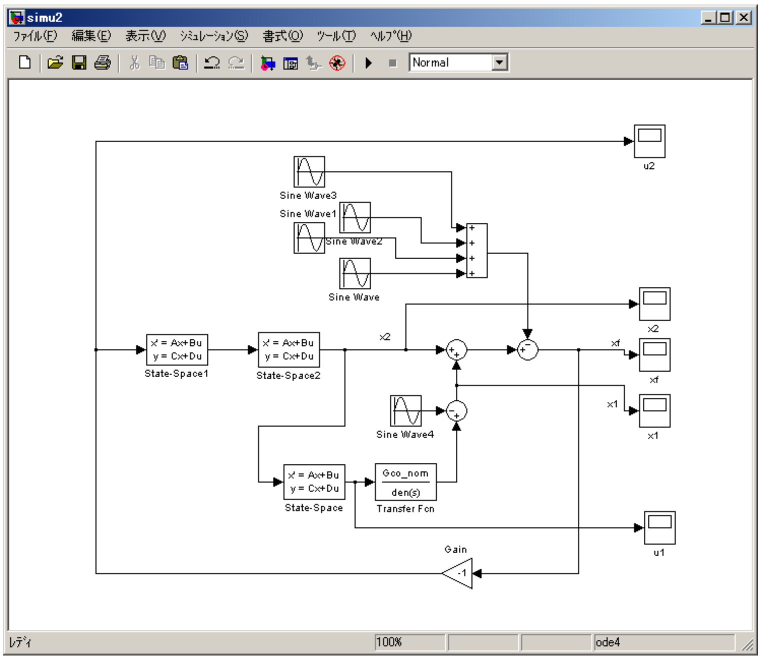
Frequency Response

MATLAB Program

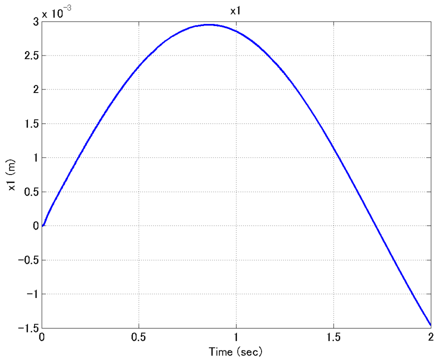
```
figure('Position',pos2)
nyquist(Lf_ss,'y')
```

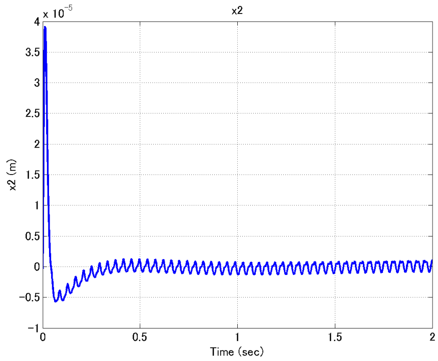


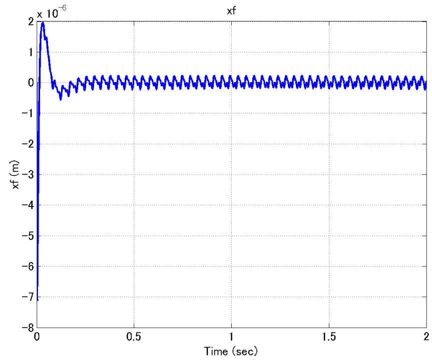
Simulation Results



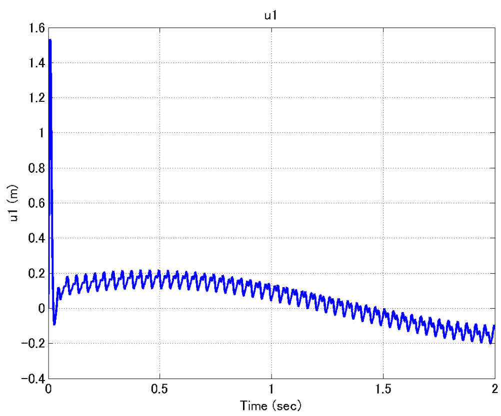
Simulation Results

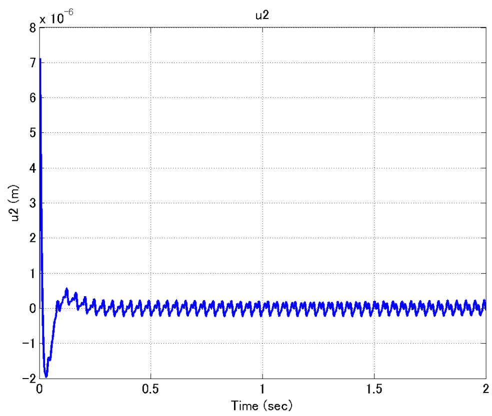






Simulation Results





Project: Report 8

Consider your dynamic system :

Using the determined uncertainty and performance characteristics, design a μ controller.

Deadline: The day before next Meeting

Please only use this email address: bevranih18@gmail.com

Thank you!