CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

As additional states were added to the control laws, the level achieved by the control law optimizations generally improved. For the full state feedback control cases, the depth control exceeded, in the authors experience, what is achievable by manual control.

Ship's control parties use more information about the state of the ship than is available from the explicit indications. Also, the success of the disturbance feedforward control suggests that averaged net force and moment would be of value to the ship's control party.

Sliding mode control provided well damped dynamics, with a robust behavior in response to changes in commanded depth. Although sliding mode control did not achieve the very low RMS errors of full state feedback, the gains which it employed were smaller and more realistic.

RECOMMENDATIONS

Although very good depthkeeping was achieved with state feedback control, the optimization schemes used resulted in control surface chatter, and very high control surface rates. To improve the quality of the model and provide more realistic planesman action several features could be added to the control laws and optimization routines:

- Investigate other sea states, speeds and sea directions
- Incorporate control surface rate limits
- Include control surface chatter in the optimization objective functions
- Use of Kalman filtering to provide state estimation and filtering
- Investigate the use of depth rate for feedback control in place of heave

The application of a new display system to an operating submarine is a major undertaking. Recommended steps to find a new manual submarine depth control paradigm are:

- Application of system identification techniques to submarine operating data to investigate the nature of the human control
- Trials of a display onboard an appropriate submarine and or a submarine dive trainer
- Use of recorded submarine operating data to provide for “instant replay” training of ship’s control personnel

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APPENDIX A

All computer code and SIMULINK® models used in this thesis are available from Professor Fotis Papoulias, Naval Postgraduate School. The computer programs and SIMULINK® models used were:

Programs:

SUBOFF.M[1]- initializes SUBOFF hydrodynamic coefficients

AXNL.M[1]- performs nonlinear Ax+E[qq;wq] calculation

SMLQR[1].M- determines MIMO sliding mode control law using Utkin's method (LQR)

WF_INI.M- reads wave data files, processes

WFORCE.M- calculates wave forces for a given depth and time

SB_INI.M- initializes model variables for MIMO vertical plane submarine model

SBI_INI.M- initializes model variables for MIMO vertical plane submarine model with integral depth control

SB_SM.M- calculates MIMO SM control law from Q matrix

SB_SS.M- calculates MIMO SM control law from sliding surface

SB_SMFF.M- determines the feed forward matrix for a given sliding mode control law

SB_PD.M-state feedback control law

SB_PDFF.M- determines the feed forward matrix for a state feedback control law

OBJ2.M - Objective function for pitch / depth feedback optimizations

OPT2A.M- Optimization program for OBJ2.M and sea state three (head seas)

OPT2B.M- Optimization program for OBJ2.M and sea state three (beam seas)

OPT2C.M- Optimization program for OBJ2.M and sea state four (head seas)

OPT2D.M- Optimization program for OBJ2.M and sea state four (beam seas)

OBJ2ff.M - Objective function for pitch / depth feedback with disturbance feedforward optimizations

OPT2FFA.M- Optimization program for OBJ2FF.M and sea state three (head seas)

OPT2FFB.M- Optimization program for OBJ2FF.M and sea state three (beam seas)

OPT2FFC.M- Optimization program for OBJ2FF.M and sea state four (head seas)

---

[1] Given after list of programs

OPT2FFD.M- Optimization program for OBJ2FF.M and sea state four (beam seas)

OBJ2I.M - Objective function for pitch / depth feedback with integral depth control optimizations

OPT2IA.M- Optimization program for OBJ2I.M and sea state three (head seas)

OPT2IB.M- Optimization program for OBJ2I.M and sea state three (beam seas)

OPT2IC.M- Optimization program for OBJ2I.M and sea state four (head seas)

OPT2ID.M- Optimization program for OBJ2I.M and sea state four (beam seas)

OBJ3.M - Objective function for full state partial distribution feedback optimizations

OPT3A.M- Optimization program for OBJ3.M and sea state three (head seas)

OPT3B.M- Optimization program for OBJ3.M and sea state three (beam seas)

OPT3C.M- Optimization program for OBJ3.M and sea state four (head seas)

OPT3D.M- Optimization program for OBJ3.M and sea state four (beam seas)

OBJ3FF.M - Objective function for full state feedback with disturbance feedforward optimizations

OPT3FFA.M- Optimization program for OBJ3FF.M and sea state three (head seas)

OPT3FFB.M- Optimization program for OBJ3FF.M and sea state three (beam seas)

OPT3FFC.M- Optimization program for OBJ3FF.M and sea state four (head seas)

OPT3FFD.M- Optimization program for OBJ3FF.M and sea state four (beam seas)

OBJ3I.M - Objective function for full state feedback with integral depth control optimizations

OPT3IA.M- Optimization program for OBJ3I.M and sea state three (head seas)

OPT3IB.M- Optimization program for OBJ3I.M and sea state three (beam seas)

OPT3IC.M- Optimization program for OBJ3I.M and sea state four (head seas)

OPT3ID.M- Optimization program for OBJ3I.M and sea state four (beam seas)

OBJ3.M - Objective function for full state feedback optimizations

OPT4A.M- Optimization program for OBJ4.M and sea state three (head seas)

OPT4B.M- Optimization program for OBJ4.M and sea state three (beam seas)

OPT4C.M- Optimization program for OBJ4.M and sea state four (head seas)

OPT4D.M- Optimization program for OBJ4.M and sea state four (beam seas)

OBJ4FF.M - Objective function for full state partial distribution feedback with disturbance feedforward optimizations

OPT4FFA.M- Optimization program for OBJ4FF.M and sea state three (head seas)

OPT4FFB.M- Optimization program for OBJ4FF.M and sea state three (beam seas)

OPT4FFC.M- Optimization program for OBJ4FF.M and sea state four (head seas)

OPT4FFD.M- Optimization program for OBJ4FF.M and sea state four (beam seas)

OBJ4I.M - Objective function for full state partial distribution feedback with integral depth control optimizations

OPT4IA.M- Optimization program for OBJ4I.M and sea state three (head seas)

OPT4IB.M- Optimization program for OBJ4I.M and sea state three (beam seas)

OPT4IC.M- Optimization program for OBJ4I.M and sea state four (head seas)

OPT4ID.M- Optimization program for OBJ4I.M and sea state four (beam seas)

OBJ7.M - Objective function for sliding mode control optimizations

OPT7A.M- Optimization program for OBJ7.M and sea state three (head seas)

OPT7B.M- Optimization program for OBJ7.M and sea state three (beam seas)

OPT7C.M- Optimization program for OBJ7.M and sea state four (head seas)

OPT7D.M- Optimization program for OBJ7.M and sea state four (beam seas)

OBJ7FF.M - Objective function for sliding mode control with disturbance feedforward optimizations

OPT7FFA.M- Optimization program for OBJ7FF.M and sea state three (head seas)

OPT7FFB.M- Optimization program for OBJ7FF.M and sea state three (beam seas)

OPT7FFC.M- Optimization program for OBJ7FF.M and sea state four (head seas)

OPT7FFD.M- Optimization program for OBJ7FF.M and sea state four (beam seas)

OBJ7I.M - Objective function for sliding mode control with integral depth control optimizations

OPT7IA.M- Optimization program for OBJ7I.M and sea state three (head seas)

OPT7IB.M- Optimization program for OBJ7I.M and sea state three (beam seas)

OPT7IC.M- Optimization program for OBJ7I.M and sea state four (head seas)

OPT7ID.M- Optimization program for OBJ7I.M and sea state four (beam seas)

OBJ7.M - Objective function for full state feedback optimizations

Models:

SMSW.M- MIMO sliding mode control submarine control model, with wave forces and trim

SMSWFF.M- Same as SMSW.M, with disturbance feedforward

SMT.M- used for determining steady state response, does not return the *x* state

PDSW.M- MIMO state feedback control submarine control model, with wave forces and trim
PDSWFF.M- Same as PDSW.M, with disturbance feedforward
PDT.M- used for determining steady state response, does not return the *x* state

Wave Force Data files:

For the first order motions / second order forces, each displacement / force is given in terms of a complex number.

Wave spectral data files
[wave frequency (rad/sec),S(ω) (), amplitude (feet), phase (rad)]

SPEC_A.TXT
SPEC_B.TXT
SPEC_C.TXT
SPEC_D.TXT

First order motions
[ω (rad/sec), $\omega_{encounter}$ (rad/sec), surge, sway, heavy, pitch, yaw, roll]

LMOT_A.TXT
LMOT_B.TXT
LMOT_C.TXT
LMOT_D.TXT

Second order forces
[ω_1 (rad/sec), ω_2 (rad/sec), F_x, F_y, F_z, M_x, M_y, M_z]

FORC_A.TXT
FORC_B.TXT
FORC_C.TXT
FORC_D.TXT

SUBOFF.M

```
function [A,B,MMI,Emat, D,WS]=suboff(U);


% SDV hydrodynamic data, TM 231-78 page 6

    ff=2; %fudge factor to make planes authority realistic for 300 ft sub

    g=32.2; %
    L=300;  % feet

    p=1.94; % slug/ft^3;



    m       = 0.018296*0.5*p*L^3;
    Iz      = 0.001084*0.5*p*L^5;
    Iy      = 0.00108*0.5*p*L^5 ;
    mxg     =-0.127467E-4;

    W=m*g;
    zgb=1;  % feet
    xgb=0;                  % feet


    Mqdot   =-0.000860*0.5*p*L^5;
    Mwdot   =-0.000561*0.5*p*L^4;
    Mq      =-0.003702*0.5*p*L^4*U;
    Mw      = 0.010324*0.5*p*L^3*U;

    Mds     =-ff*0.002409*0.5*p*L^3*U^2;
    Mdb     =-Mds/4;

    Zqdot   =-0.000633*0.5*p*L^4;
    Zwdot   =-0.014529*0.5*p*L^3;

    Zq      =-0.007545*0.5*p*L^3*U;
    Zw      =-0.013910*0.5*p*L^2*U;

    Zds     =-ff*0.005603*0.5*p*L^2*U^2;
    Zdb     =Zds/2;



% define mass matrix, compute mass matrix inverse

mm=eye(4);
mm(1,1)=m-Zwdot;
mm(1,2)=-Zqdot;
mm(2,1)=-Mwdot;
mm(2,2)=Iy-Mqdot;
```

```
A=zeros(4,4);
A(1,1)=Zw;
A(1,2)=m*U+Zq;
A(2,1)=Mw;
A(2,2)=Mq;
A(2,3)=-zgb*W;
A(3,2)=1;
A(4,1)=1;
A(4,3)=-U;

B=[ Zdb Zds;Mdb Mds;0 0;0 0];

MMI=inv(mm);

A=MMI*A;
B=MMI*B;
Emat=MMI(1:2,1:2)*[m*zgb,0;0,-m*zgb];

% diameter and surface area calculation

D=L/8.575;

WS=67.651*(L/13.9792)^2;
```

AXNL.M

```
function ax=axnl(x)

global Amat Emat

n=max(size(x));

a=Amat;
a(4,1)=Amat(4,1)*cos(x(3));
x(3)=sin(x(3));

ax=a*x;
ax(1:2)=ax(1:2)+Emat*[x(2)^2;x(2)*x(1)];
```

SMLQR.M

```
function [k,s,ks,e]=smlqr(a,b,q)

%       [k,s,ks,e]=smlqr(a,b,q) determines the sliding
%       mode control law for the system
%       xdot=a*x+b*u where
%       u=-kx-kn*satsgn(sigma) and
%       sigma=s*x.  q is a positive definite
%       symmetric weighting matrix
%       used in assigning error weights
%       (LQR) to the states.  Uses Utkin's method
%       as detailed in Hawkinson pp10-17



[n,m]=size(b);

% do transformation if required
if norm(b(m+1:n,1:m))>eps^0.5

        [t,b1]=qr(b);
        b1=b1(1:m,1:m);
        t=t';
else
        t=eye(n);
        b1=b(1:m,1:m);
end

q=t*q*t';
a=t*a*t';

q11=q(1:m,1:m);
q12=q(1:m,m+1:n);
q21=q(m+1:n,1:m);
q22=q(m+1:n,m+1:n);

a11=a(1:m,1:m);
a12=a(1:m,m+1:n);
a21=a(m+1:n,1:m);
a22=a(m+1:n,m+1:n);

as=a22-a21*inv(q11)*q12;
qs=q22-q21*inv(q11)*q12;

kt=are(as,a21*inv(q11)*(a21') ,qs);

c2=(inv(q11)*(q12+a21')*kt)';

k=-[inv(b1)*(a11+c2'*a21),inv(b1)*(a12+c2'*a22)]*t;

s=rref([eye(m); c2]'*t)';
```

```
ks=-inv(s'*b);

e=eig([a+[b1;zeros(n-m,m)]*k*t']);
```

APPENDIX B

MAPLE® Solutions

Determination of MIMO state feedback control steady state

Determination of MIMO sliding mode control steady state

INITIAL DISTRIBUTION LIST

1.	Defense Technical Information Center 8725 John J. Kingman Rd., STE 0944 Ft. Belvoir, VA 22060-6218	2
2.	Dudley Knox Library Naval Postgraduate School 411 Dyer Rd. Monterey, CA 93943-5101	2
3.	Chairman, Code MEMc Department of Mechanical Engineering Naval Postgraduate School Monterey, CA 93943-5000	1
4.	Mr. Randy Dean Johns Hopkins University Applied Physics Laboratory Mail Stop 13-N422 Johns Hopkins Road Laurel, MD 20723-609	2
5.	Naval Engineering Curricular Office, Code 34 Naval Postgraduate School Monterey, CA 93943-5000	1
6.	Professor F. A. Papoulias, Code MEPa Department of Mechanical Engineering Naval Postgraduate School Monterey, CA 93943-5000	5
7.	LT John Tolliver HCR 67 Box 64 Loma, MT 59460	4