# Output Feedback Control of Underwater Vehicles Using Nonlinear State Observer

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# Outline

- Summary of Previous Work
- Problem Formulation
- Output Feedback Control
- Dive Plane Equation of Motion
- Observer Design
- Controller Design
- Simulation Results
- Conclusion

# Summary of previous work

- Effects of actuator dynamics
  - Actuators in UUVs such as thrusters, rudders have time lag and this tends to degrade system performance and make quick and precise control difficult.
  - Thruster dynamics has significant influence on the dynamics of vehicle.
  - Investigation of the influence of the rudder dynamics on the system response. However, since UUVs are operated in low speed, rudder dynamics does not influence the UUV dynamics.
  - Rudder dynamics is substantial only at high speed such as in torpedo application.

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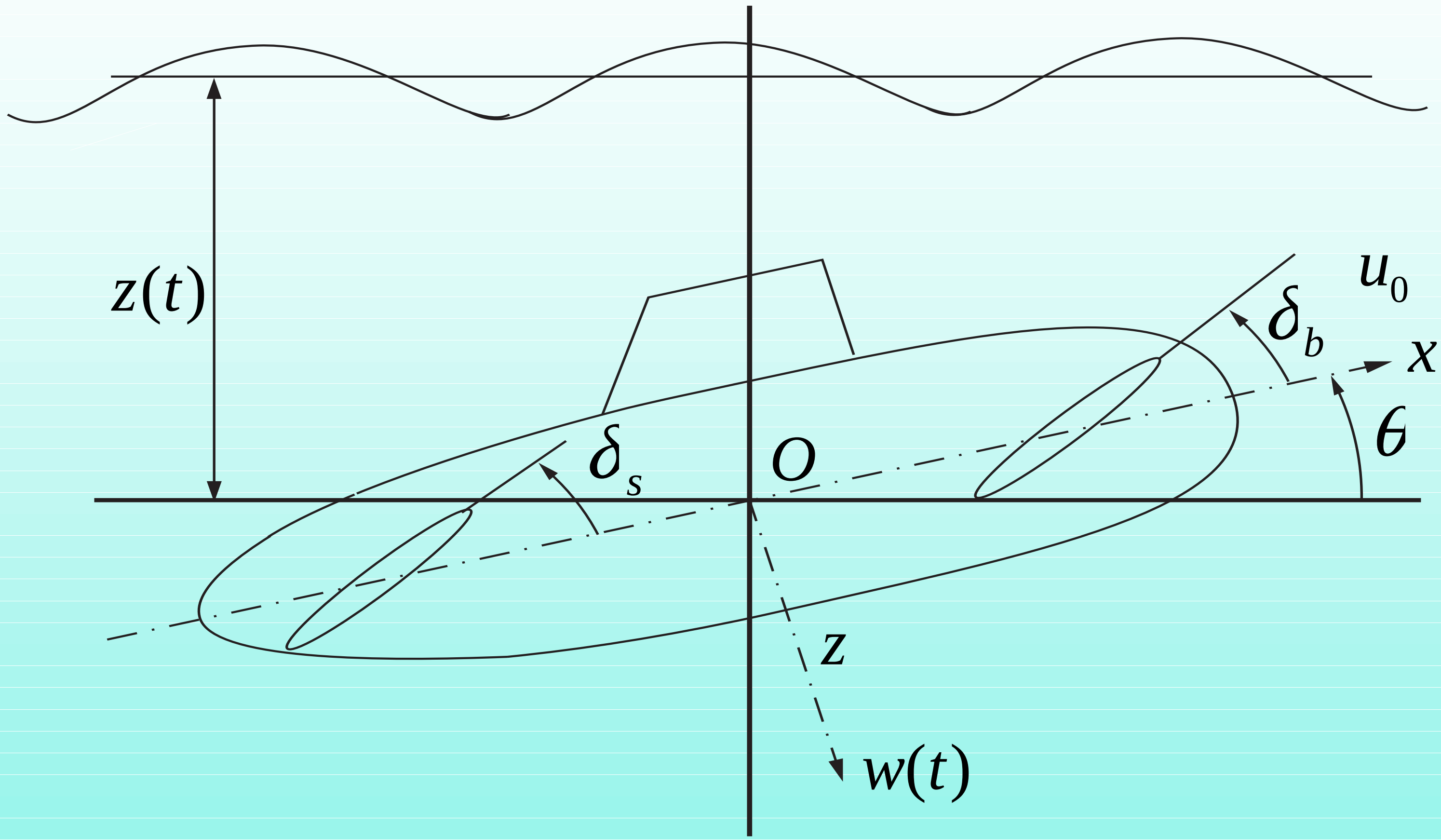
# Problem Formulation

- Sliding Mode Controller
  - Advantages
    - Capable of handling nonlinear systems
    - Robust to uncertainties/parameter variation
  - Disadvantages
    - All states measurement required
    - Occurrence of undesirable chattering phenomena
  - Chattering can be avoided by including boundary layer
  - Design of nonlinear observer for state estimation

# Output Feedback Control

- Healey(NPS) et.al.
  - Design of Robust Observer
  - Sliding Mode Control with estimated states
- Fossen(NIT) et.al.
  - Nonlinear Observer from the kinematic relationship with additional acceleration measurements
  - Adaptive Control with estimated states
- Nonlinear State observer using Sliding Mode

# Dive Plane Equation of Motion



# Dive Plane Equation of Motion(Cont'd)

$$m[\dot{w} - uq - x_G \dot{q} - z_G q^2]$$
$$= z_{\dot{q}} \dot{q} + z_{\dot{w}} \dot{w} + z_q uq + z_w w + u^2 (z_b \delta_b + z_s \delta_s)$$

$$I_y \dot{q} - m[x_G(\dot{w} - uq) - z_G(\dot{u} + wq)]$$
$$= M_{\dot{q}} \dot{q} + M_{\dot{w}} \dot{w} + M_q uq + M_w uw + u^2 (M_b \delta_b + M_s \delta_s)$$
$$-(x_G mg - x_B B)\cos\theta - (z_G mg - z_B B)\sin\theta$$

$$\dot{\theta} = q$$

$$\dot{z} = w\cos\theta - u\sin\theta$$

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# Dive Plane Equation of Motion(Cont'd)

## State Space Form

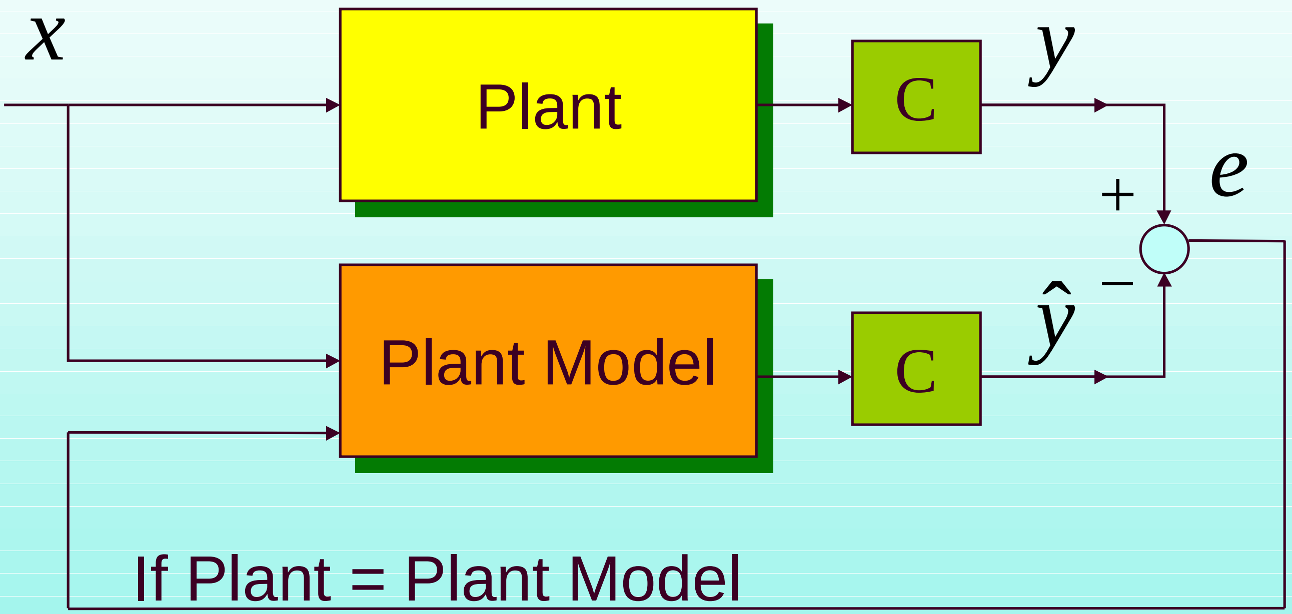
$$\begin{bmatrix} \dot{w} \\ \dot{q} \\ \dot{\theta} \\ \dot{z} \end{bmatrix} = \begin{bmatrix} a_{11}u & a_{12}u & a_{13} & 0 \\ a_{21}u & a_{22}u & a_{23} & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & -u & 0 \end{bmatrix} \begin{bmatrix} w \\ q \\ \theta \\ z \end{bmatrix} + \begin{bmatrix} b_{11}u^2 & b_{12}u^2 \\ b_{21}u^2 & b_{22}u^2 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \delta_b \\ \delta_s \end{bmatrix}$$

$$+ \begin{bmatrix} F_d \cos\theta \\ M_d \cos\theta \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} e_{11}q^2 + e_{12}qw \\ e_{21}q^2 + e_{22}qw \\ 0 \\ 0 \end{bmatrix}$$

## Output Equation

$$\begin{bmatrix} z \\ q + \theta \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \end{bmatrix} \begin{bmatrix} w \\ q \\ \theta \\ z \end{bmatrix}$$

# Observer Design




If Plant = Plant Model

then $y = \hat{y}$

# Observer Design(Cont'd)

$$\dot{x} = Ax + f(t,x) + B[u(t) + v(t)]$$

$$y = Cx$$

## Assumptions

A1) The system is detectable so that we can find G.
The spectrum of $A - GC = 0$ is in the LHP

A2) There exists $Q \in R^{n\times m}$ ,symmetric and positive definite,
and function $h$ and $w$ such that:

$$f(t,x) = P^{-1}C^T h(t,x)$$

$$Bv(t) = P^{-1}C^T w(t)$$

where $A_0{}^T P + PA_0 = -Q$

A3) Let $\xi(t,x) = h(t,x) + w(t,x)$. Then, there exists a positive scalar
Such that: $\|\xi(t,x)\| < \rho$

# Observer Design(Cont'd)

Sliding Mode Observer

$$\dot{\hat{x}} = A_o\hat{x} + Gy + S(\hat{x}, y) + Bu$$

where
$$S(\hat{x}, y) = \begin{cases} -\dfrac{P^{-1}C^T Ce}{\|Ce\|}\rho & \text{for} \quad e \neq 0 \\ 0 & \text{for} \quad e = 0 \end{cases}$$

- We measure the depth and the pitch rate.
- The pitch angle can be obtained by integrating pitch rate.

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# Controller Design

- PD Controller

$$\begin{bmatrix} \delta_b \\ \delta_s \end{bmatrix} = \begin{bmatrix} K_{11} & K_{12} & K_{13} & K_{14} \\ K_{21} & K_{22} & K_{23} & K_{24} \end{bmatrix} \begin{bmatrix} w - w_{com} \\ q - q_{com} \\ \theta - \theta_{com} \\ z - z_{com} \end{bmatrix}$$

- Sliding Mode Controller

Switching surface

$$\sigma(t,x) = [\sigma_1(t,x) \quad \ldots \quad \sigma_m(t,x)]^T = 0$$

Reaching condition

$$\frac{d}{dt}\left(\frac{1}{2}\sigma^T \sigma\right) = \sigma^T \dot{\sigma} < 0$$

# Controller Design(Cont'd)

Gradient of $\sigma$

$$\frac{\partial \sigma(t,x)}{\partial x} = S(t,x)$$

Control input

$$u = u_{eq_{nom}} + \bar{u}$$

$$\begin{cases} u_{eq_{nom}} = -[S(t,x)B]^{-1}(S(t,x)Ax + \dfrac{\partial \sigma}{\partial t}) \\ \bar{u} = -[S(t,x)B]^{-1}\eta\, sign(\sigma) \end{cases}$$

# Simulation results

- Nominal forward speed 6 knot
- Bounds on nonlinear terms

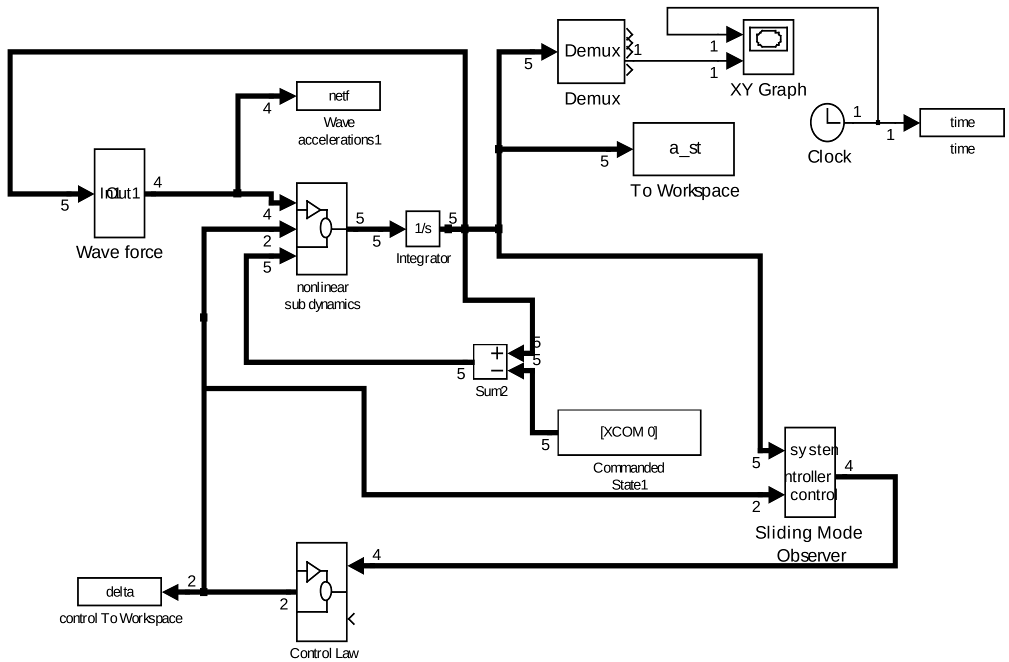
$|\theta| < 10^o$ : pitch angle

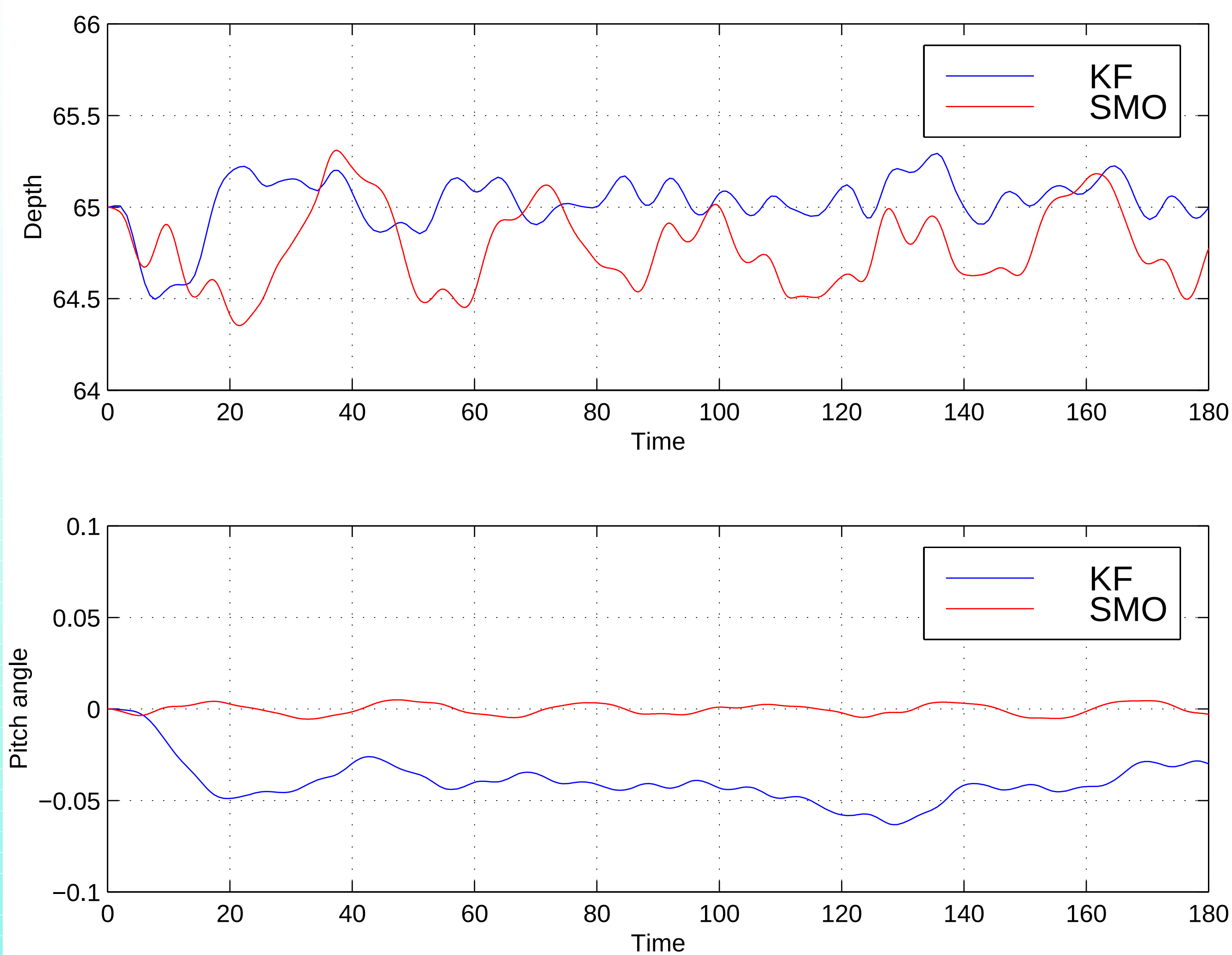
$|q| < 0.2 \quad rad/\sec$ : pitch rate

$|w| < 1.5 \quad ft/s$ : heave speed

- Include bounds of wave force

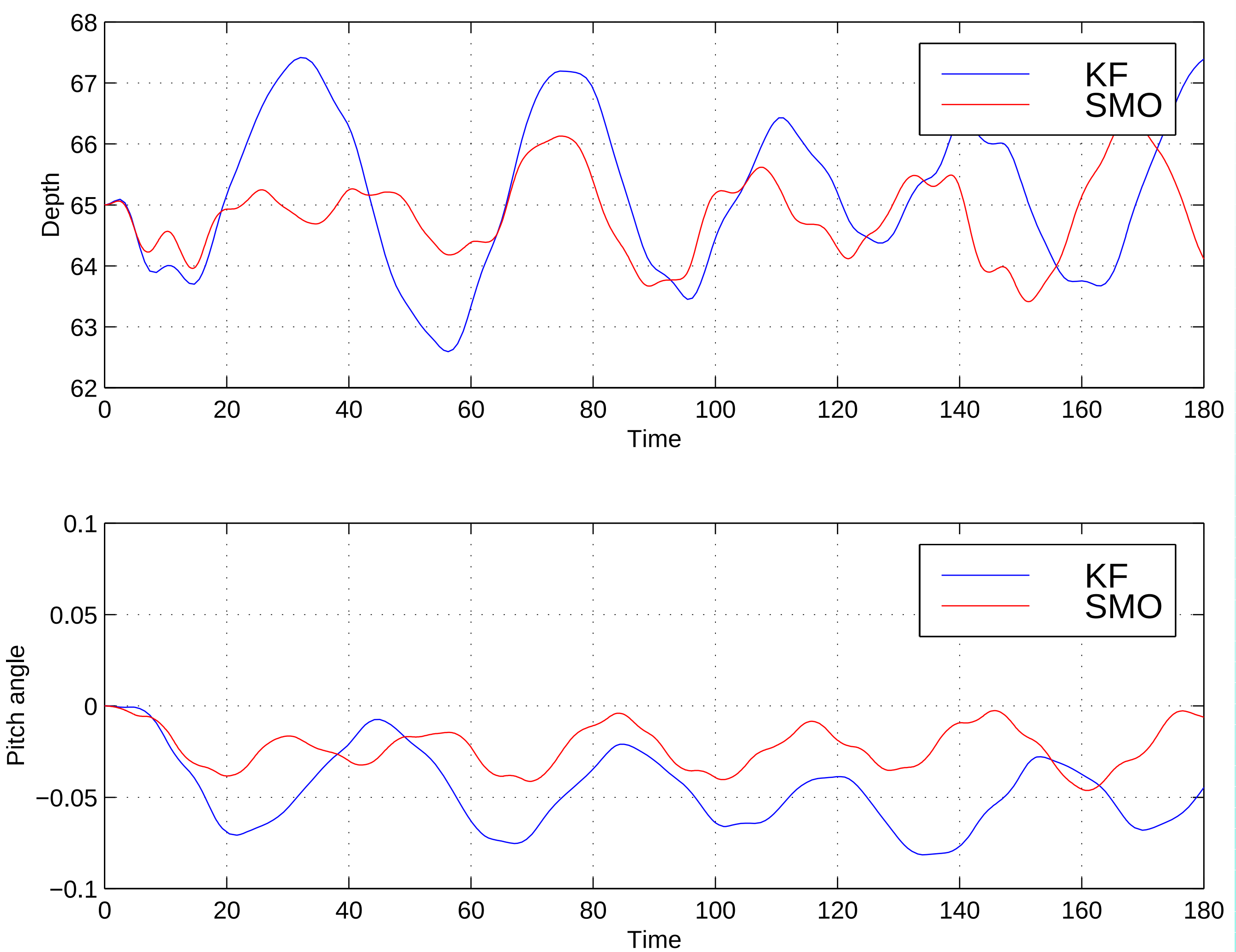
# Simulink Model



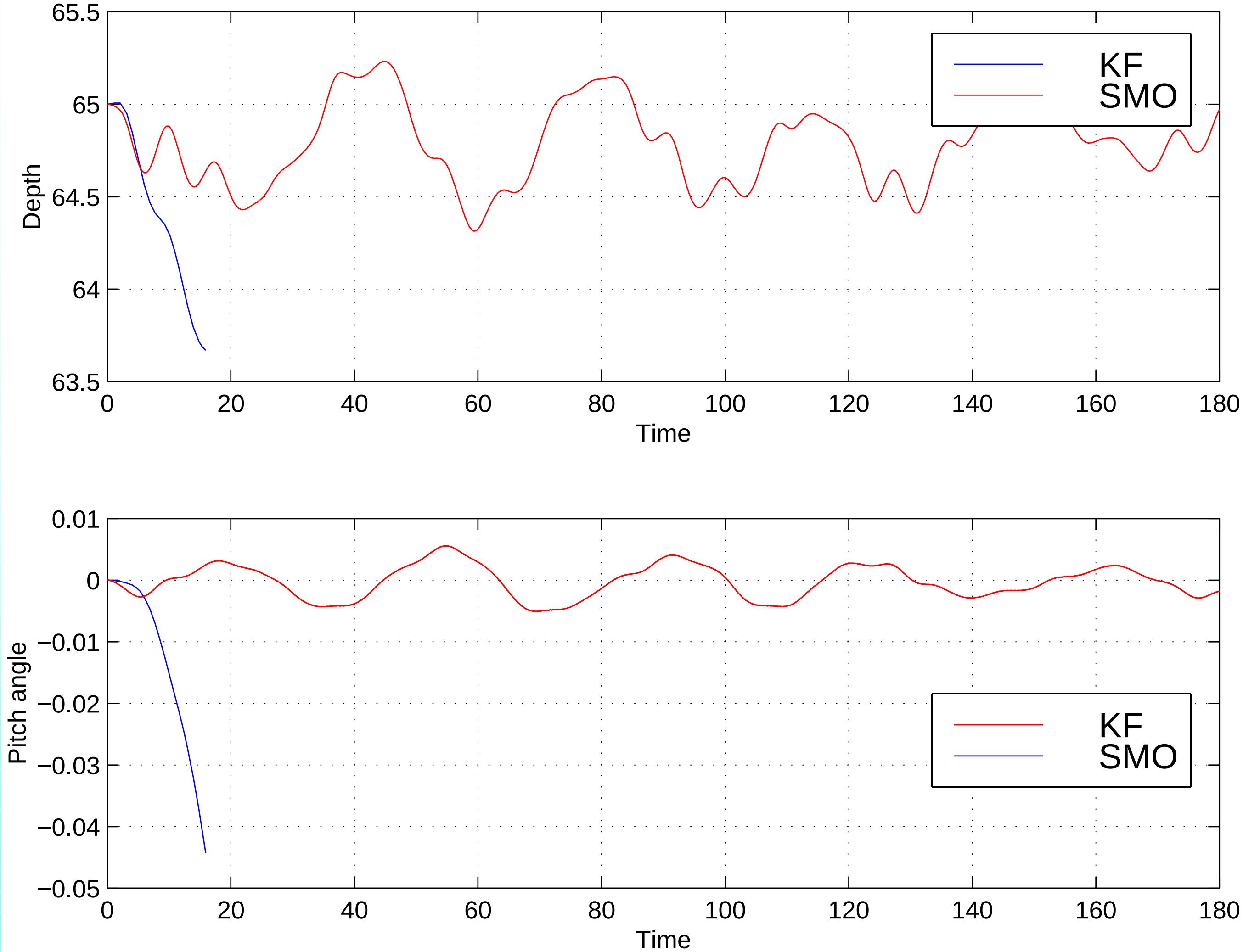



Depth and pitch response to 65ft dive command at sea state 3

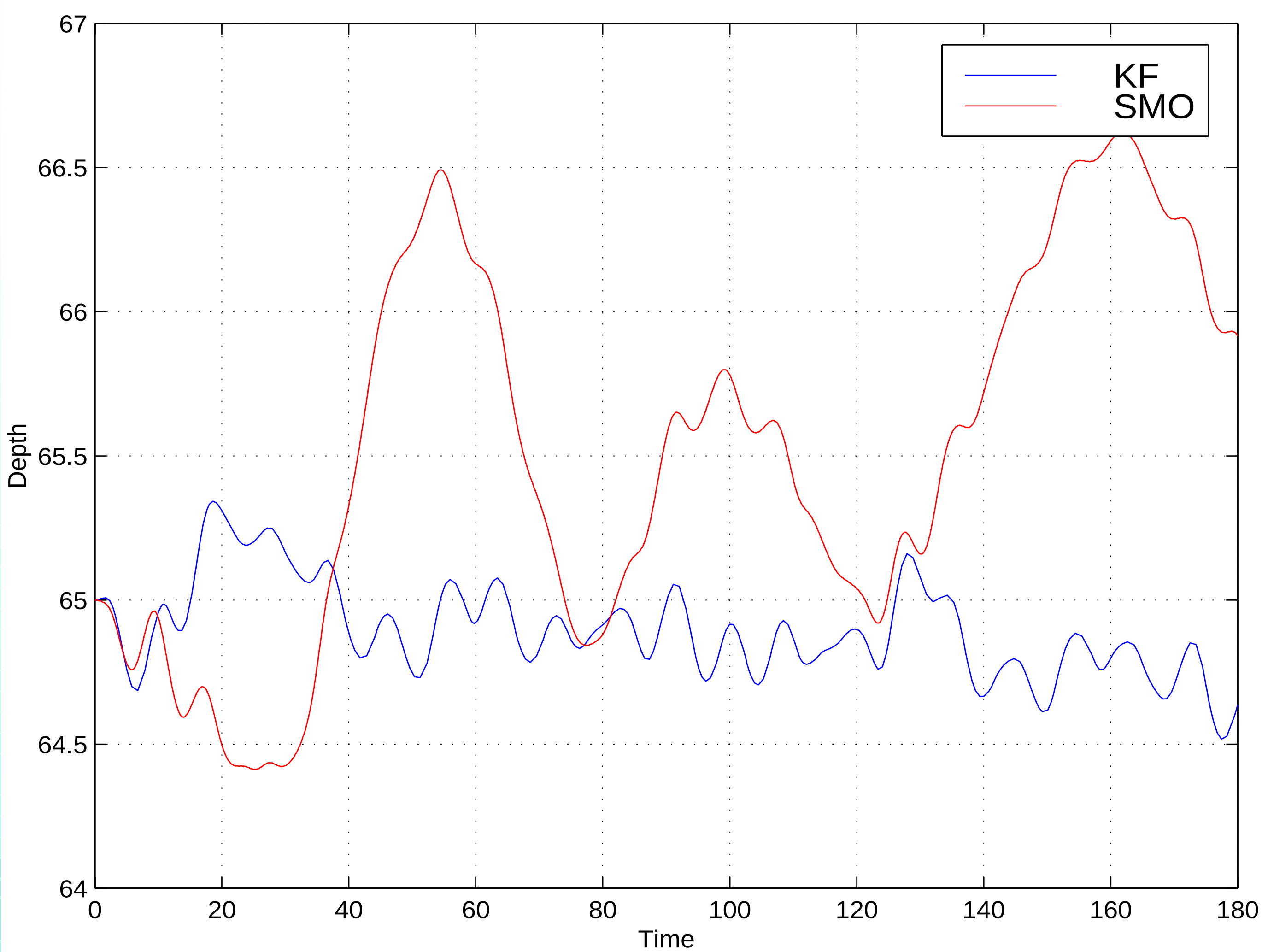
-PD control-



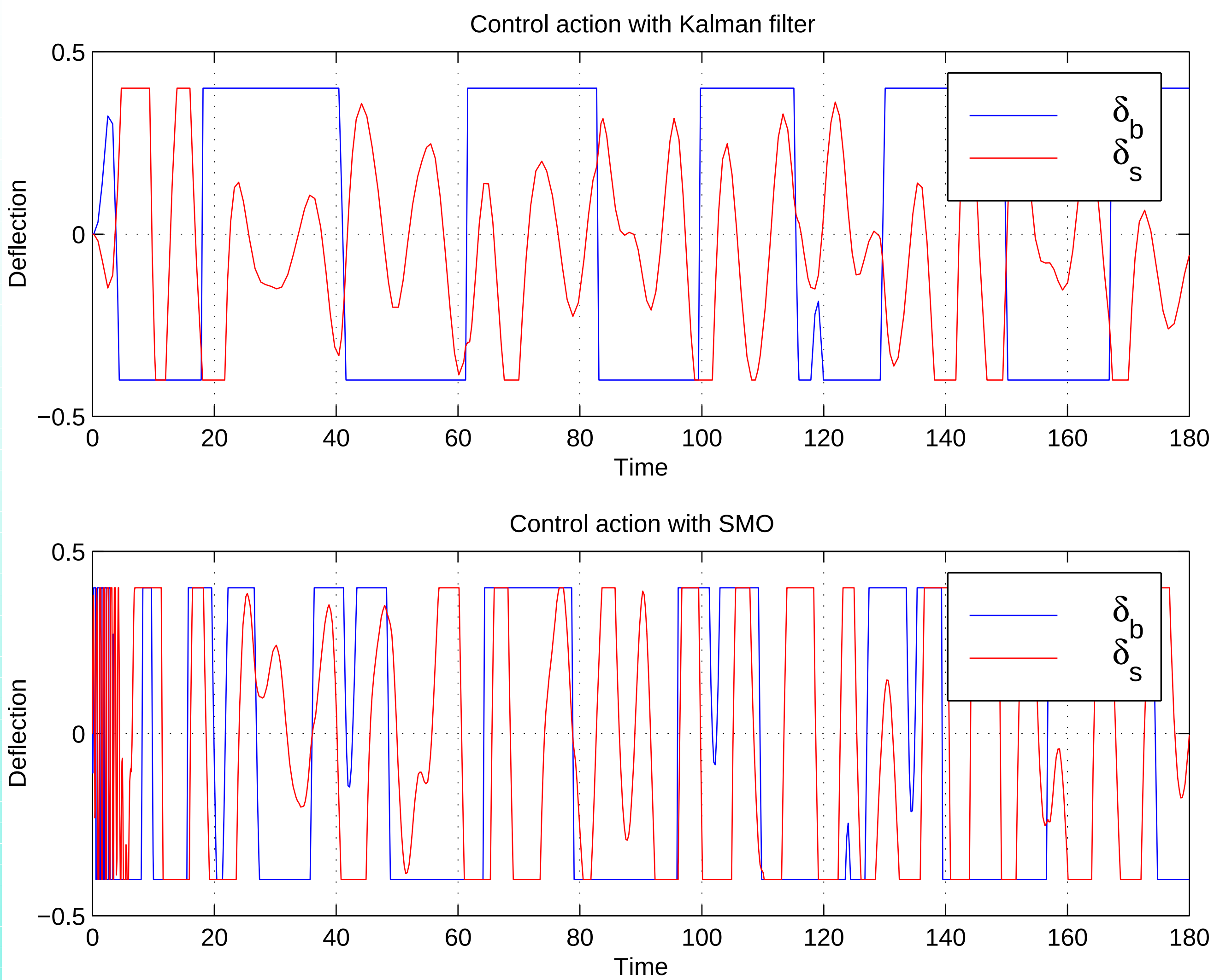

Depth and pitch response to 65ft dive command at sea state 4
-PD control-




Depth and pitch response to 65ft dive command
with 30% parameter variation
-PD control-




Depth and pitch response to 65ft dive command at sea state 3
-Sliding mode control-

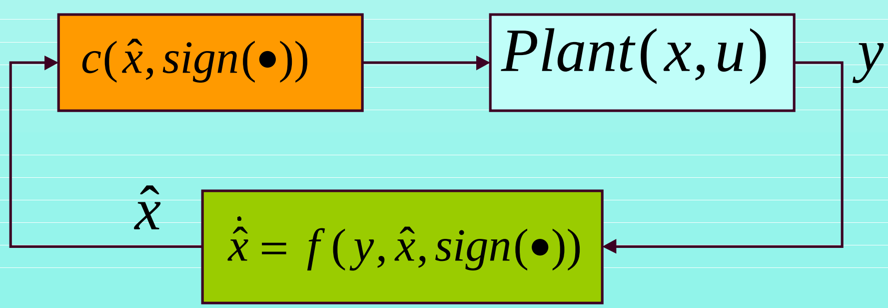



# Comparison of control action

# SMC and SMO Combination

- Unexpected results are observed when SMC(Sliding Mode Controller) and SMO(Sliding Mode Observer) are combined.
- Possible problem
  - nested discontinuities

$$f = sign(sign(u))$$



# Conclusion

- Sliding mode observer is designed and applied in the dive plane of submarine in order to estimate linear velocity component(heave velocity).
- It is compared with the Kalman filter estimator which is based on linearized dynamics and showed better performance in terms of robustness to wave disturbance, model parameter uncertainties, and parameter variation.
- When,however, the SMC and SMO are combined, undesirable results are obtained. More investigation is required.
- This sliding mode observer can be applied to fault detection algorithm in replace of Kalman filter.
- It takes more computational time in estimating the states when sliding mode observer is used. More efficient computational algorithm needs to be investigated.

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