Disturbance Estimation and Rejection based Control of Marine Vessels

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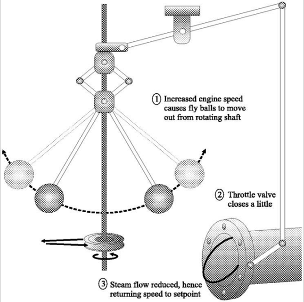
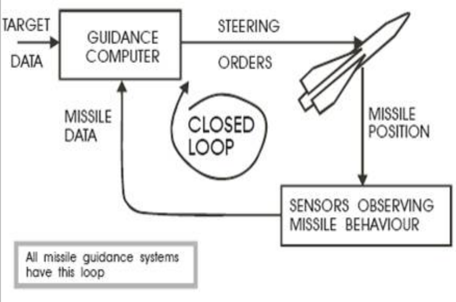
Feedback Control

- **Feedback control systems are present everywhere; within inside and outside.**
- **Known by various names: Feedback control systems, Automatic control systems, Servomechanisms, Regulators etc.**
- **Highly interdisciplinary engineering discipline**

Feedback Control Systems

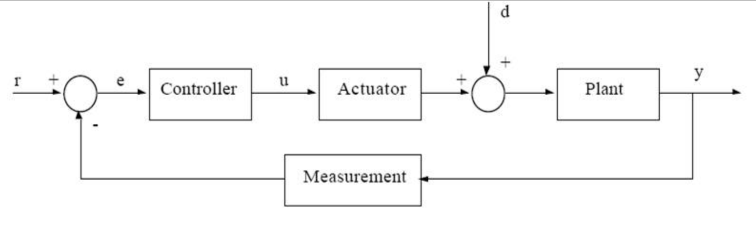




Composition of Feedback Control System

- **Plant:** Physical system to be controlled
- **Actuator:** Device to provide actuating power
- **Sensor:** Measures the output
- **Controller:** Generates actuating signal through manipulation of error signal (Most important part from Control engineers point of view)

Feedback Control Systems

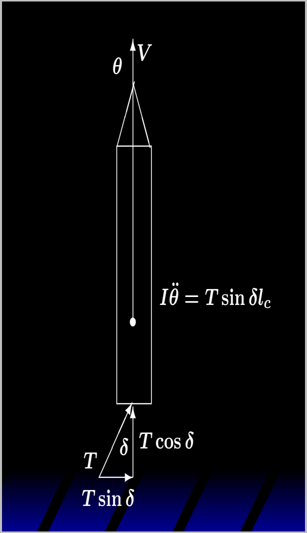


Magic of Feedback

- Changes system dynamics
  - Stability
  - Desired behavior
- Reduced sensitivity to uncertainties and disturbance
- Linearization
- Smoothing and filtering (system induced noise and distortion are reduced)

Magic of Feedback

Stabilizing the unstable system



A Good Design

A good design should ensure:

- **Stability**: Feedback system must be stable with good stability margin [relative stability]
- **Performance**: Satisfy specifications
- **Robustness**: Assurance of stability and performance in the presence of uncertainties, disturbances and measurement inaccuracies

Trade-offs:

- More stable systems offer poorer performance (Stability at the cost of performance)
- More stable systems require larger control efforts.

Disturbance Rejection

Methods to deal with uncertainties and disturbances:

- **Classical-high loop gain**
- **Integral control action**
- **Robust designs-characterizing the uncertainties and disturbances as**
  - **deterministic**
  - **polynomial**
  - **bounded**
  - **stochastic**
- **Disturbance estimation and compensation**

High Gain Control

Concept:

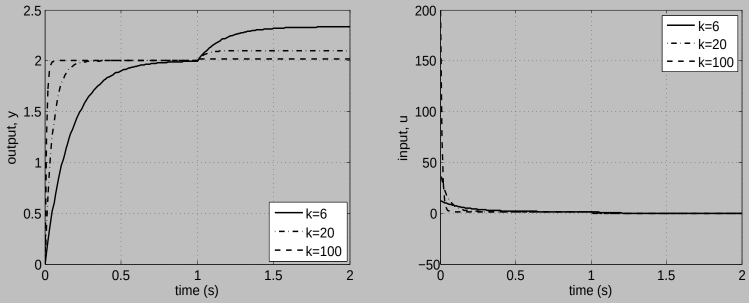
Consider the dynamics	:	$\dot{y} = f(y) + u + d$
Objective	:	$y(t) \rightarrow y^\star(t)$
Control Law	:	$u(t) = -f(y) + \dot{y}^\star + k(y^\star - y)$
Tracking error	:	$e(t) = y^\star(t) - y(t)$
Closed loop dynamics	:	$\dot{e} + ke = -d$
For constant $d = 1$	:	$e(\infty) = -\frac{1}{k}$

High Gain Control

Data:

$f(y) = -0.7y$, $y^\star(t) = 2$, $d(t) = 2$ at $t = 1$ sec, $k = 6, 20, 100$

Performance of high gain controller



High gain is needed to suppress the effect of disturbance.

Integral Control

Concept:

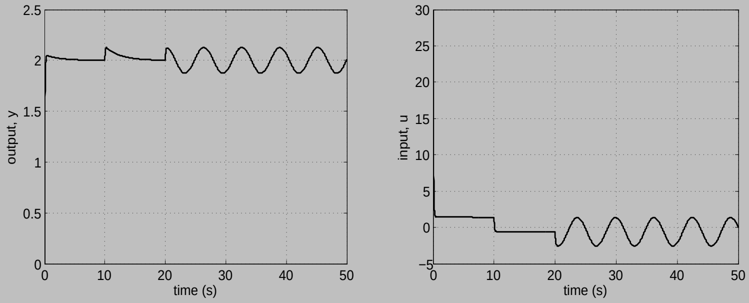
Consider the dynamics	:	$\dot{y} = f(y) + u + d$
Objective	:	$y(t) \rightarrow y^\star(t)$
Control Law	:	$u(t) = -f(y) + \dot{y}^\star + k_p(y^\star - y) + \int_0^t (y^\star - y) d\tau$
Tracking error	:	$e(t) = y^\star(t) - y(t)$
Closed loop dynamics	:	$\ddot{e} + k_p \dot{e} + k_i e = -\dot{d}$
For constant d	:	$e(\infty) = 0$
For constant $\dot{d} = 1$	:	$e(\infty) = \frac{1}{k_i}$

Integral Control

Data:

$f(y) = -0.7y$, $y^{\star}(t) = 2$, $d(t) = 2$ at $t = 10$ *sec* and $2 + 2sin(t)$ at $t = 20sec$, $k_p = 6$, $k_i = 15$

Performance of integral controller



Integral control can only remove effect of constant disturbance.

ESO based Control

Introduction
Extended State Observer
Ship Autopilot Design
Concluding Remarks

Concept: Active disturbance rejection

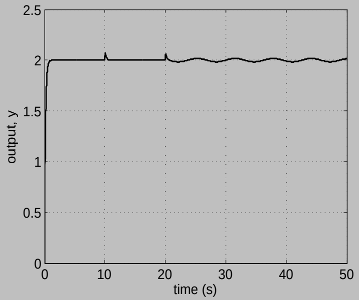
Consider the dynamics	:	$\dot{y} = f(y) + u + d$
Objective	:	$y(t) \to y^{\star}(t)$
Control Law	:	$u(t) = -f(y) + \dot{y}^{\star} + k(y^{\star} - y) - d$
Tracking error	:	$e(t) = y^{\star}(t) - y(t)$
Closed loop dynamics	:	$\dot{e} + ke = 0$

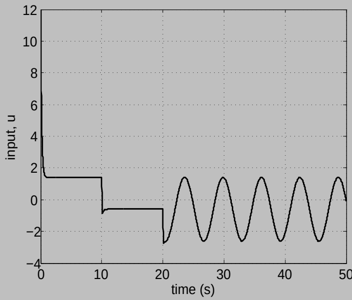
ESO based Control

Data:

$f(y) = -0.7y$, $y^{\star}(t) = 2$, $d(t) = 2$ at $t = 10$ *sec* and $2 + 2sin(t)$ at $t = 20sec$, $k = 6$.

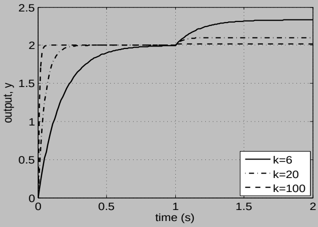
Performance of ESO based controller



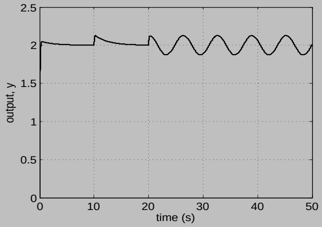


ESO based disturbance estimation and compensation results in accurate tracking of reference.

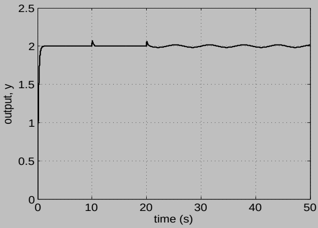
Comparative Performance



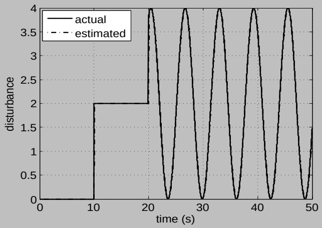
(a) High gain control



(b) Integral control



(c) ESO based control



(d) Disturbance estimation

Active vs Passive

Passive Disturbance Rejection

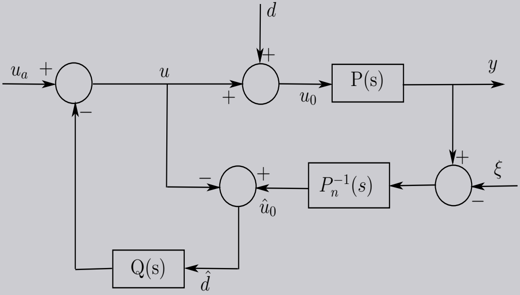
To reject/attenuate the effect of disturbances through feedback mechanism. Controllers may not reject disturbance directly, completely and fast enough.

Active Disturbance Rejection

Directly eliminate the effect of disturbances through estimation of disturbance.

Disturbance Estimation and Rejection

The idea is to treat the effects of system uncertainties, nonlinearities, unknown dynamics, cross-coupling effects and external disturbances as a TOTAL or COMPOSITE disturbance acting on the system, estimate it and then to use the estimate in the nominal controller to cancel the effect of the disturbance.



Disturbance Estimation Techniques

Some disturbance estimation techniques:

1. Unknown Input Observer (UIO)
2. Equivalent Input Disturbance method (EID)
3. Disturbance Observer (DO)
4. Perturbation Observer (PO)
5. Time Delay Control (TDC)
6. Uncertainty and Disturbance Estimator (UDE)
7. Predictive Filtering (PF)
8. Sliding Mode State and Perturbation Observer (SMSPO)
9. Extended State Observer (ESO)

Extended State Observer

Extended State Observer

1. **Estimates the effect of uncertainties and disturbances along with the states**
2. **Regards all factors affecting the plant, i.e., nonlinearities, uncertainties, and the external disturbances as a TOTAL disturbance**
3. **The total disturbance is treated as an extended state to be observed**
4. **Relatively independent of mathematical model of the plant**

Concept of ESO

- **System dynamics:**

$$\begin{aligned} \ddot{y} &= a(y, \dot{y}, w) + bu \\ &= [a(y, \dot{y}, w) + (b - b_o)u] + b_o u \\ &= d + b_o u \end{aligned}$$

- **Control strategy:**

$$u = \frac{1}{b_o}\left[-d + \ddot{y}^{\star} + k_1(y^{\star} - y) + k_2(\dot{y}^{\star} - \dot{y})\right]$$

- **Closed-loop dynamics:** $e_{c_1} = y^{\star} - y$

$$\frac{d^2 e_{c_1}}{dt^2} + k_2 \frac{de_{c_1}}{dt} + k_1 e_{c_1} = 0$$

Concept of ESO

- System dynamics:

$$\ddot{y} = d + b_o u$$

- State space model: $x = [y \ \dot{y}]^T$

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= d + b_o u \\ y &= x_1 \end{aligned}$$

- Extended order system: $[x_3 \triangleq d]$

$$\begin{aligned} \dot{x}_1 &= x_2 \\ \dot{x}_2 &= x_3 + b_o u \\ \dot{x}_3 &= h \\ y &= x_1 \end{aligned}$$

Concept of ESO

- **Extended State Observer**

$$
\begin{aligned}
\dot{\hat{x}}_1 &= \hat{x}_2 + \beta_1 g_1(e_{o_1}) \\
\dot{\hat{x}}_2 &= \hat{x}_3 + \beta_2 g_2(e_{o_1}) + b_o u \\
\dot{\hat{x}}_3 &= \beta_3 g_3(e_{o_1}) \\
\hat{y} &= \hat{x}_1
\end{aligned}
$$

- **Nonlinear gain function**

$$
g_i(e_{o_1}, \alpha_i, \delta) = \begin{cases} |e_{o_1}|^{\alpha_i} sign(e_{o_1}), & |e_{o_1}| > \delta \\ \frac{e_{o_1}}{\delta^{1-\alpha_i}}, & |e_{o_1}| \leq \delta \end{cases}
$$

$$
i = 1, 2, 3
$$

Concept of ESO

- **Control strategy:**

$$u = \frac{1}{b_o}\left[-d + \ddot{y}^\star + k_1(y^\star - y) + k_2(\dot{y}^\star - \dot{y})\right]$$

- **ESO based control:**

$$u = \frac{1}{b_o}\left[-\hat{x}_3 + \dot{x}_2^\star + k_1(x_1^\star - \hat{x}_1) + k_2(x_2^\star - \hat{x}_2)\right]$$

Linear and Nonlinear ESO

- **Nonlinear ESO (NESO): Nonlinear gain function**

$$g_i(e_{o_1}, \alpha_i, \delta) = \begin{cases} |e_{o_1}|^{\alpha_i} sign(e_{o_1}), & |e_{o_1}| > \delta \\ \frac{e_{o_1}}{\delta^{1-\alpha_i}}, & |e_{o_1}| \leq \delta \end{cases}$$
$$i = 1, 2, 3$$

- **Linear ESO (LESO): Linear gain**

$$g_i(e_{o_1}, \alpha_i, \delta) = e_{o_1}; \quad i = 1, 2, 3$$

- **LESO essentially represents a special case of the nonlinear ESO if one chooses the NESO parameters, α_is, as unity.**

Ship Autopilot Design

Design of Ship Autopilot

- **Autopilot based control is one of the most important aspects used on-board marine vessels.**
- **Transformation from purely mechanical or manual mode to microprocessor based control: reduced manpower, higher reliability, optimum performance, comfort to the crew, adequate economy in the form of reducing journey time especially in bad weather conditions.**
- **Ship by virtue of being at sea is inherently always under the influence of various environmental disturbances caused by wind, tides, waves, underwater sea currents, and change of depth under keel varying over a wide range depending on locations on earth and climatic conditions.**
- **The dynamics of ship is also affected by ship sailing order such as trim, loading, ballast, speed etc.**

Mathematical Model

The first order Nomoto model:

$$\frac{r(s)}{\delta(s)} = \frac{K}{(1+Ts)}$$

In terms of yaw angle

$$\frac{\psi(s)}{\delta(s)} = \frac{K}{s(1+Ts)}$$

Differential equation:

$$T\ddot{\psi} + \dot{\psi} = K\delta$$

where ψ is the yaw angle, r is the yaw rate, δ is the rudder deflection, T is the effective yaw rate time constant and K represents the static yaw rate gain.

Mathematical Model

The model is modified to include nonlinear steering condition wherein the heading angle rate $\dot{\psi}$ term is replaced by a nonlinear function $H(\dot{\psi})$.

$$T\ddot{\psi} + H(\dot{\psi}) = K\delta$$

where

$$H(\dot{\psi}) = \alpha_0 + \alpha_1\dot{\psi} + \alpha_2\dot{\psi}^2 + \alpha_3\dot{\psi}^3$$

The steering model

$$\frac{\delta}{\delta_c} = \frac{1}{1 + s\tau_\delta}$$

Disturbances

One of the challenges in control of marine vessels is the disturbances caused by waves on the vessel. The surface vessels are always under the effect of external environmental disturbances due to waves, winds and underwater ocean currents. Broadly, these disturbances are classified as:

- **High Frequency Disturbances**: Caused due to the first order induced waves

  $$\frac{y(s)}{\eta(s)} = h(s) = \frac{K_w s}{s^2+2\zeta\omega_e s+\omega_e^2}$$

- **Low Frequency Disturbances**: Low frequency disturbances are created due to slow varying wind, currents and second order wave induced motions.

  $$\frac{y_{lf}(s)}{w(s)} = h_{lf}(s) = \frac{1}{s+0.01}$$

Parameter variations/Uncertainties

Another challenge in control of marine vessels is the parameter variations and or their uncertainty.

Parametric Variation:

Ship's motion is nonlinear and time-variant as the parameters are varying with changing conditions. The quantities T, K etc are hydrodynamic parameters dependent on ship navigating speed, loading condition and weather conditions determined by waves, winds, tidal, water depth and so on.

IOL Controller

The Input-Output Linearization (IOL) is one of the most prominent approaches towards design of a controller for nonlinear systems

- **Ship dynamics**:

  $$\ddot{\psi} = -\frac{1}{T}H(\dot{\psi}) + \frac{1}{T}K\delta_c$$

- **IOL controller**:

  $$\delta_c = \frac{1}{K}(H(\dot{\psi}) + T\nu)$$

- **Outer-loop control**:

  $$\nu = \ddot{\psi}^\star + m_1(\psi^\star - \psi) + m_2(\dot{\psi}^\star - \dot{\psi})$$

- **Output tracking error dynamics**:

  $$\frac{d^2 e_{c1}}{dt^2} + m_2 \frac{de_{c1}}{dt} + m_1 e_{c1} = 0; \qquad e_{c1}(t) = \psi^\star(t) - \psi(t)$$

ESO based Controller

The Input-Output Linearization (IOL) is one of the most prominent approaches towards design of a controller for nonlinear systems

Ship dynamics:

$$\ddot{\psi} = a + b\delta_c + d'$$

Defining total disturbance:

$$\ddot{\psi} = a_{10}\psi + a_{20}\dot{\psi} + b_0 u + d$$

The IOL controller:

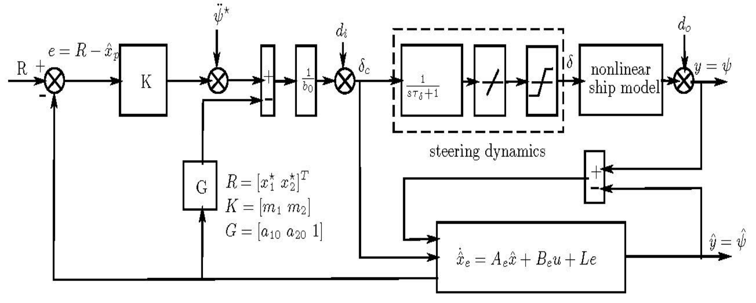
$$u = \delta_c = \frac{1}{b_0}\left[-a_{10}\psi - a_{20}\dot{\psi} - d + \ddot{\psi}^\star + m_1(\psi^\star - \psi) + m_2(\dot{\psi}^\star - \dot{\psi})\right]$$

ESO based controller:

$$u = \frac{1}{b_0}\left[-a_{10}\hat{x}_1 - a_{20}\hat{x}_2 - \hat{x}_3 + \dot{x}_2^\star + m_1(x_1^\star - \hat{x}_1) + m_2(x_2^\star - \hat{x}_2)\right]$$

Ship Autopilot

Functional block diagram of the ESO-based controller



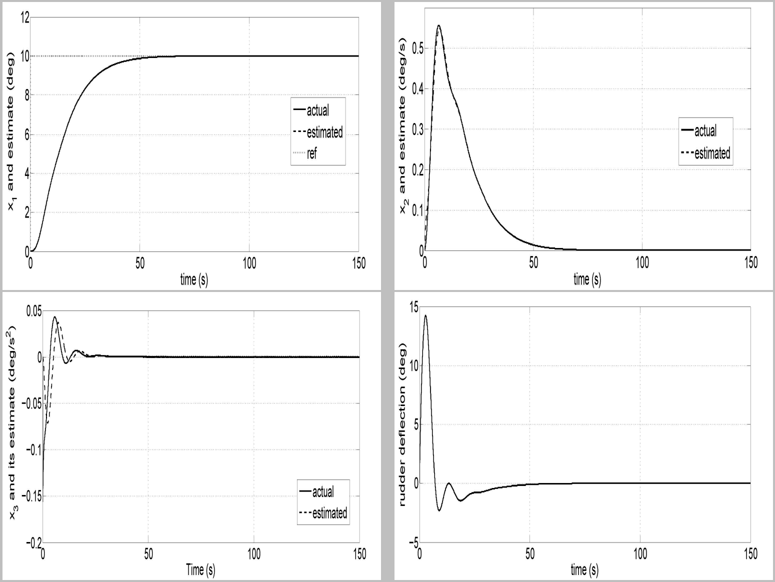
Simulation Data

Simulations are carried out to verify the performance of the ESO based controller.

- Time constant, T, and gain, K, are taken as 29 and 0.35.
- The values of α_0 and α_2 are taken as zero and α_3 is taken as 0.2378.
- Controller gains m_1 and m_2 are obtained pole placement at $(1 + \frac{\tau_c}{2}s)^2$ with τ_c=16 sec.
- ESO gains, β_is, are obtained by placing the observer poles at $(1 + \frac{\tau_o}{3}s)^3$ with $\tau_o = \tau_c/7$.
- The initial conditions for ESO as well as the plant are taken as zero.
- Step reference yaw angle $\psi^\star = 10^o$.
- Actual uncertainty is computed as $d = \dddot{\alpha} - a_{1o}\alpha - a_{2o}\dot{\alpha} - a_{3o}\ddot{\alpha} - b_o u$.

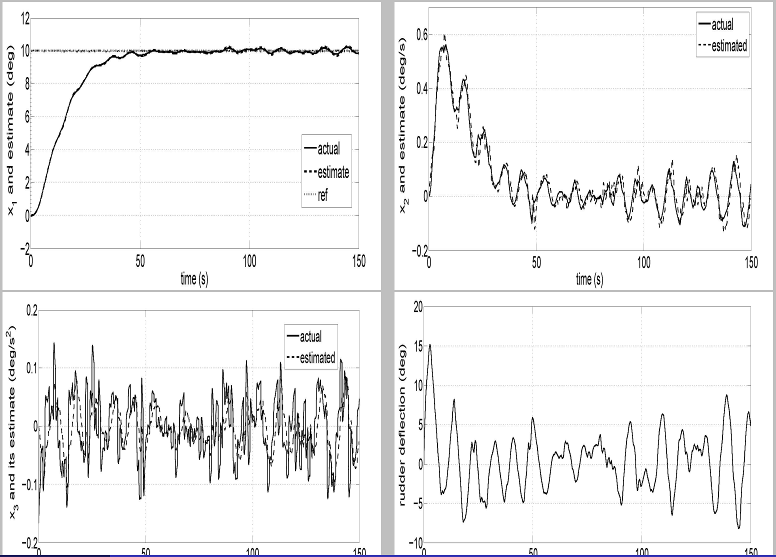
Simulation Results

Performance without uncertainties and disturbances



Simulation Results

Performance in the presence of uncertainties, disturbances, and measurement noise



Comparison with Existing Design

Performance comparison of the proposed design with some well-known designs existing in the literature

Designs

- IOL controller
- Lyapunov based Controller
- PID Control and
- Proposed ESO based design

For valid comparison, the plant data is taken the same in simulation of all the controllers.

Comparison with Existing Design

IOL Controller

$$u = \frac{1}{b_0}\left[-a_{10}\psi - a_{20}\dot{\psi} - d + \ddot{\psi}^\star + m_1(\psi^\star - \psi) + m_2(\dot{\psi}^\star - \dot{\psi})\right]$$

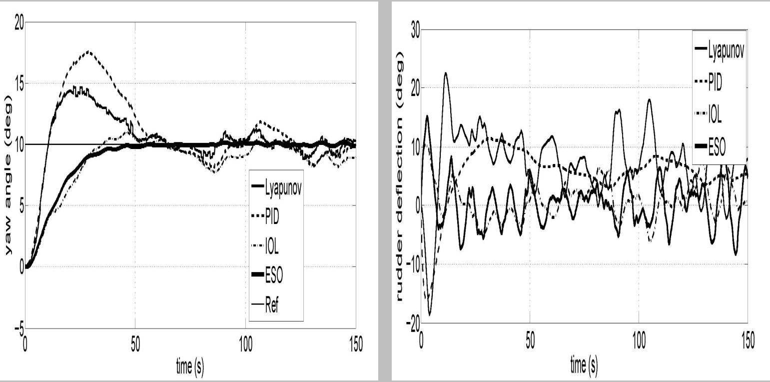
Lyapunov based Controller

$$\begin{aligned} u &= m\dot{v} + dv - K_d s \\ V(s) &= \frac{1}{2}ms^2; \quad s = \tilde{r} + 2\lambda\tilde{\psi} + \lambda^2\int_0^t \tilde{\psi}(\tau)d\tau \\ v &= r - s = r_d - 2\lambda\widetilde{\psi} - \lambda^2\int_0^t \widetilde{\psi}(\tau)d\tau \end{aligned}$$

PID Control

$$u = \frac{k_c}{sT_c}(sT_c + 1)\frac{sT_c' + 1}{sT_o + 1}$$

Performance Comparison



Swarup Das and S. E. Talole, "Robust Steering Autopilot Design for Marine Surface Vessels," *IEEE Journal of Oceanic Engineering*, **Vol. 41, No. 1, Oct 2016, pp 913-922**

Concluding Remarks

What does one need to know about a plant in order to control it effectively?

Thank You