Passivity Based Control

applied to

Dynamic Positioning of Ships

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Passivity Based Control using port-Hamiltonian formulation

Port- Hamiltonian Structure

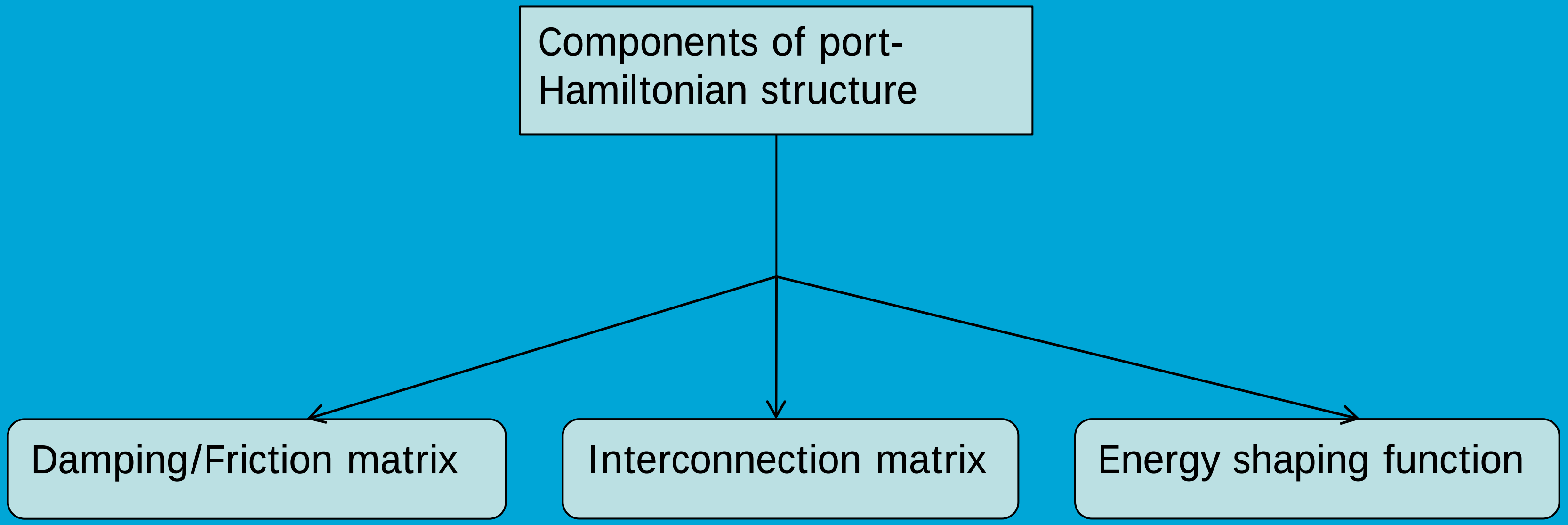

Figure 1. A description of port-Hamiltonian structure.

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Passivity Based Control using port-Hamiltonian formulation

1. Port-Hamiltonian model of a system

$$\dot{x} = (\mathfrak{I} - \mathfrak{R})\partial H(x) + g(x)u, \qquad (1)$$

$$y = g^{T}(x)\partial H(x) \qquad (2)$$

Interconnection matrix

Damping matrix

Energy shaping/function

Port-Hamiltonian passive output

Passivity Based Control using port-Hamiltonian formulation

2. IDA-PBC methodology

Desired closed loop dynamics

$$\dot{x} = (\mathfrak{I}_d - \mathfrak{R}_d)\partial H_d(x), \qquad (3)$$

Equate (2) and (3), and solve for "u"

Control law

$$u = (g^T g)^{-1} g^T ((\mathfrak{I}_d - \mathfrak{R}_d)\partial H_d(x) - (\mathfrak{I} - \mathfrak{R})\partial H, \qquad (4)$$

Mathematical Model of Ship

1. Model in Cartesian coordinates

$$\begin{bmatrix} \dot{\eta} \\ \dot{\nu} \end{bmatrix} = \begin{bmatrix} O_3 & J(\psi) \\ O_3 & -M^{-1}D \end{bmatrix} \begin{bmatrix} \eta \\ \nu \end{bmatrix} + \begin{bmatrix} O_3 \\ M^{-1} \end{bmatrix} \tau + \begin{bmatrix} O_3 \\ M^{-1}J^T(\psi) \end{bmatrix} \qquad (5)$$

$$\eta = [x \quad y \quad \psi]^T, \qquad \nu = [u \quad v \quad r]^T$$

$$M = M^T = \begin{bmatrix} m_{11} & 0 & 0 \\ 0 & m_{22} & m_{23} \\ 0 & m_{32} & m_{33} \end{bmatrix} \geq 0,$$

$$D = D^T = \begin{bmatrix} d_{11} & 0 & 0 \\ 0 & d_{22} & d_{23} \\ 0 & d_{32} & d_{33} \end{bmatrix} \geq 0$$

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Mathematical Model of Ship

2. Model in port-Hamiltonian (energy) coordinates

Coordinate transformation

$$q = \eta, \qquad p = M\nu$$

Choice of energy shaping

$$H(q,p) = \frac{1}{2} q^T K q$$

(5)

$$\begin{bmatrix} \dot{q} \\ \dot{p} \end{bmatrix} = \left(\begin{bmatrix} O_3 & J(q_3) \\ -J^T(q_3) & O_3 \end{bmatrix} - \begin{bmatrix} O_3 & O_3 \\ O_3 & D \end{bmatrix} \right) \partial H + \begin{bmatrix} O_3 \\ I_3 \end{bmatrix} \tau + \begin{bmatrix} O_3 \\ J^T(q_3) \end{bmatrix} b \quad (6)$$

$$q = [q_1 \quad q_2 \quad q_3]^T, \quad p = [p_1 \quad p_2 \quad p_3]^T$$

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Dynamic Positioning Problem

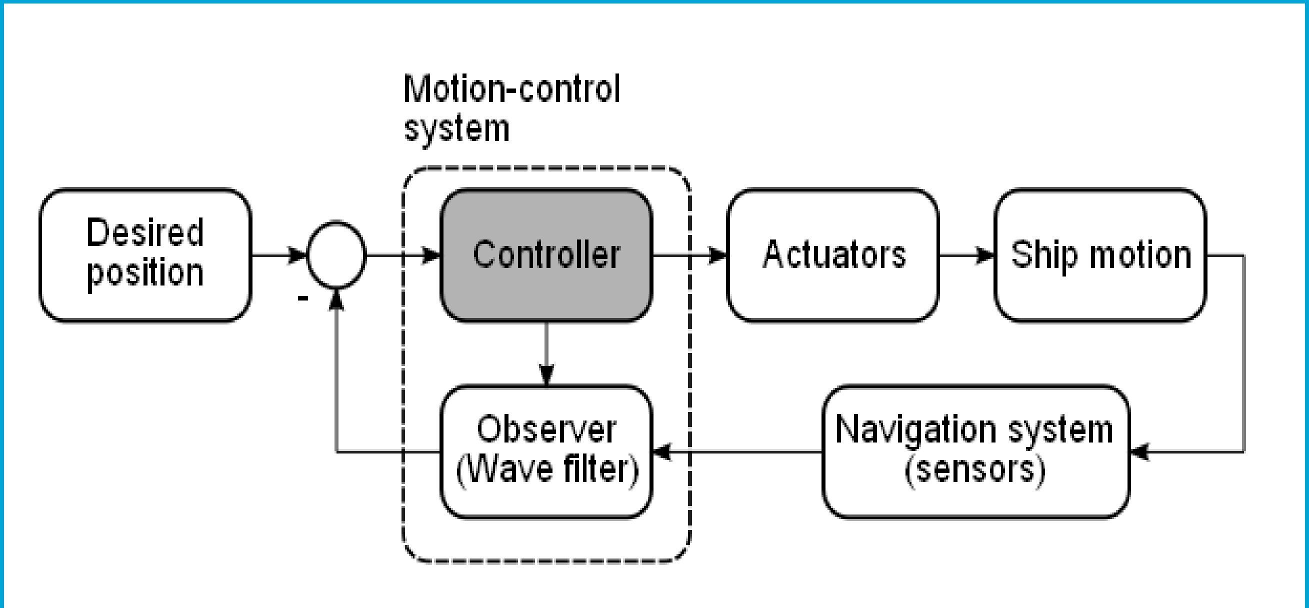

Figure 2. A description of motion control system.

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Dynamic Positioning Problem

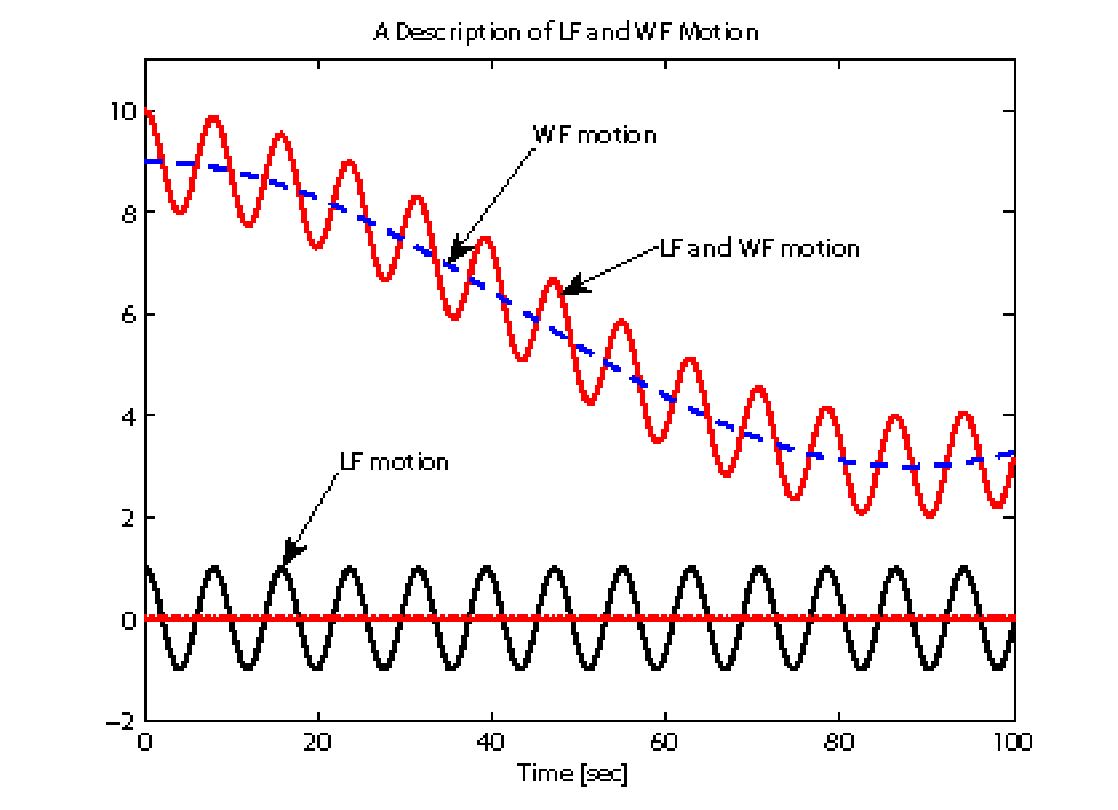

Figure 3. A description of LF and WF motions

Quadratic vs Trigonometric energy shaping

Two different energy functions

$$H_{d1}(q,p)=\frac{1}{2}q^T K q+\frac{1}{2}p^T M^{-1}p \quad (7)$$

$$H_{d2}(q,p)=\frac{1}{2}q_{12}^T C_{12} q_{12}+c_3(1-\cos q_3)+\frac{1}{2}p^T M^{-1}p, \quad (8)$$

Quadratic energy shaping

Trigonometric energy shaping

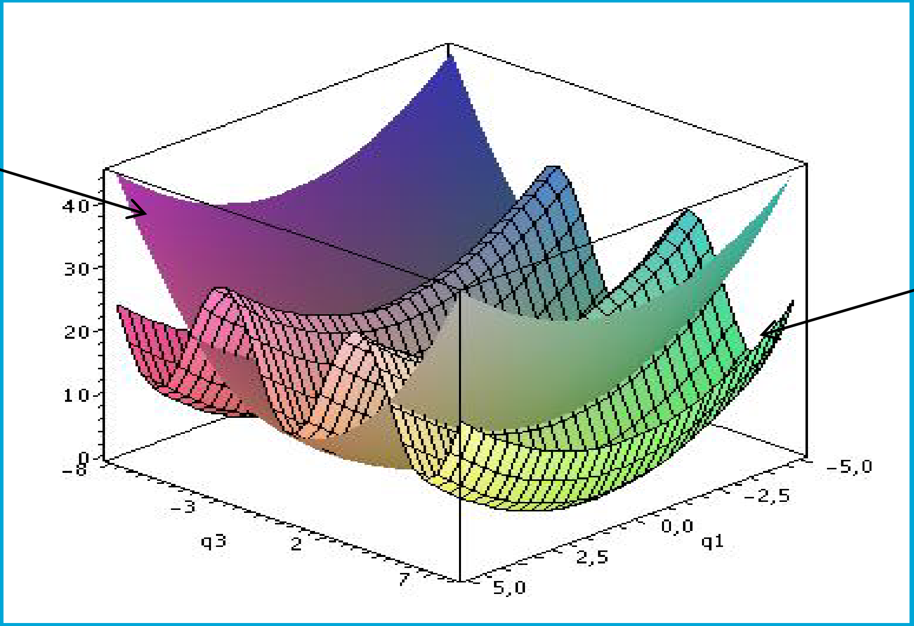

Figure 4. A description of quadratic and trigonometric energy shapings.

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Quadratic vs Trigonometric energy shaping

Effect on the performance of the controller and the choice of the control law

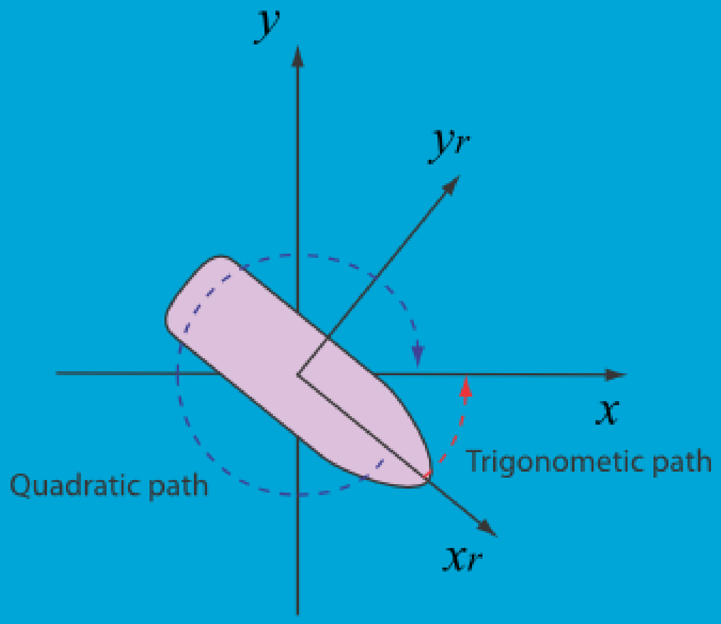

Figure 5. A description of the effect of the energy shaping on the heading control of the ship.

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Family of Passivity Based Controllers

1. Static quadratic controller

A nonlinear output feedback PD-controller with a feed forward term →

$$H_{d1}(q,p) = \frac{1}{2} q^T K q + \frac{1}{2} p^T M^{-1} p$$

$$\tau_{sq} = -J^T(q_3)(Kq + b) - K_D J^T(q_3)\dot{q} \qquad (9)$$

2. Static trigonometric controller

A nonlinear output feedback PD-controller with a feed forward term →

$$H_{d2}(q,p) = \frac{1}{2} q_{12}^T C_{12} q_{12} + c_3(1 - \cos q_3) + \frac{1}{2} p^T M^{-1} p,$$

$$\tau_{st} = -J^T(q_3)\left(C \begin{bmatrix} q_1 \\ q_2 \\ \sin q_3 \end{bmatrix} + b\right) - K_D J^T(q_3)\dot{q}. \qquad (10)$$

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Family of Passivity Based Controllers

- Quadratic vs trigonometric energy shaping

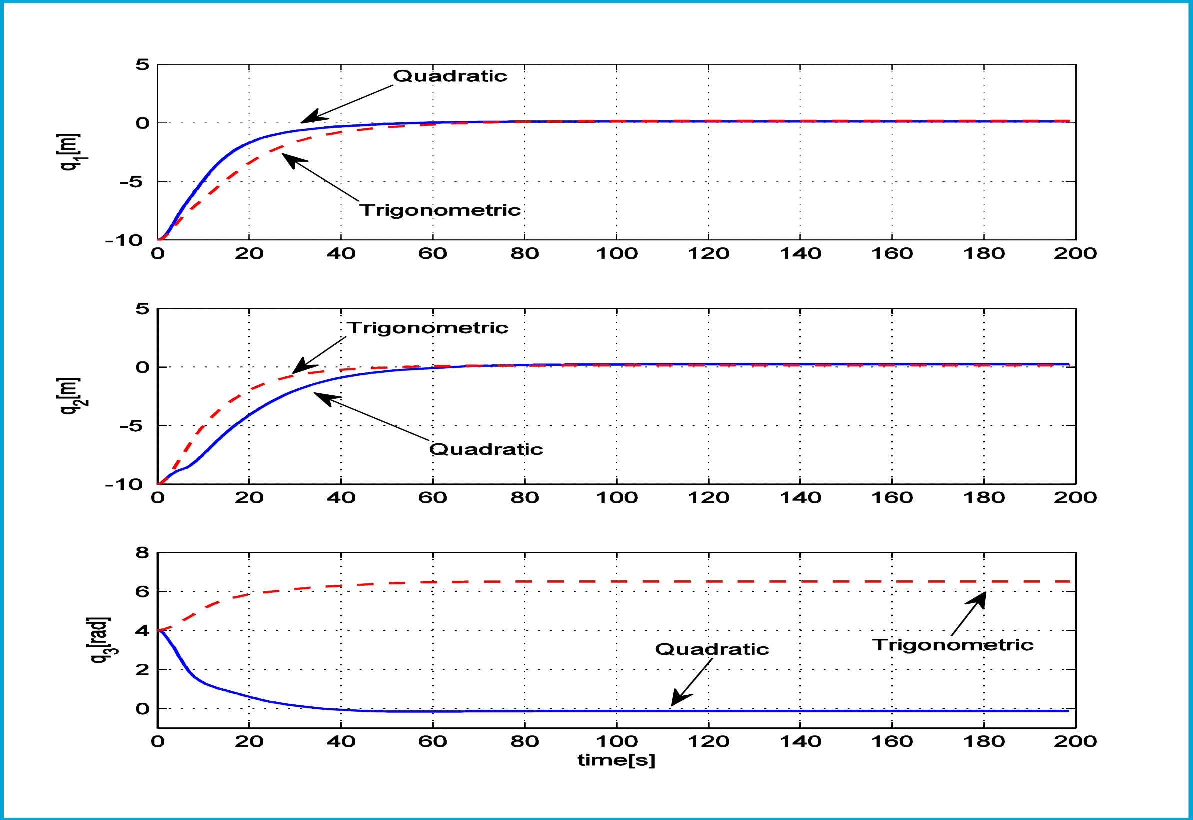

Figure 6. Ship position coordinates, q1 and q2, and heading angle q3 , for the static quadratic controller (solid line) and the trigonometric controller (dashed line).

Family of Passivity Based Controllers

- Quadratic vs trigonometric energy shaping

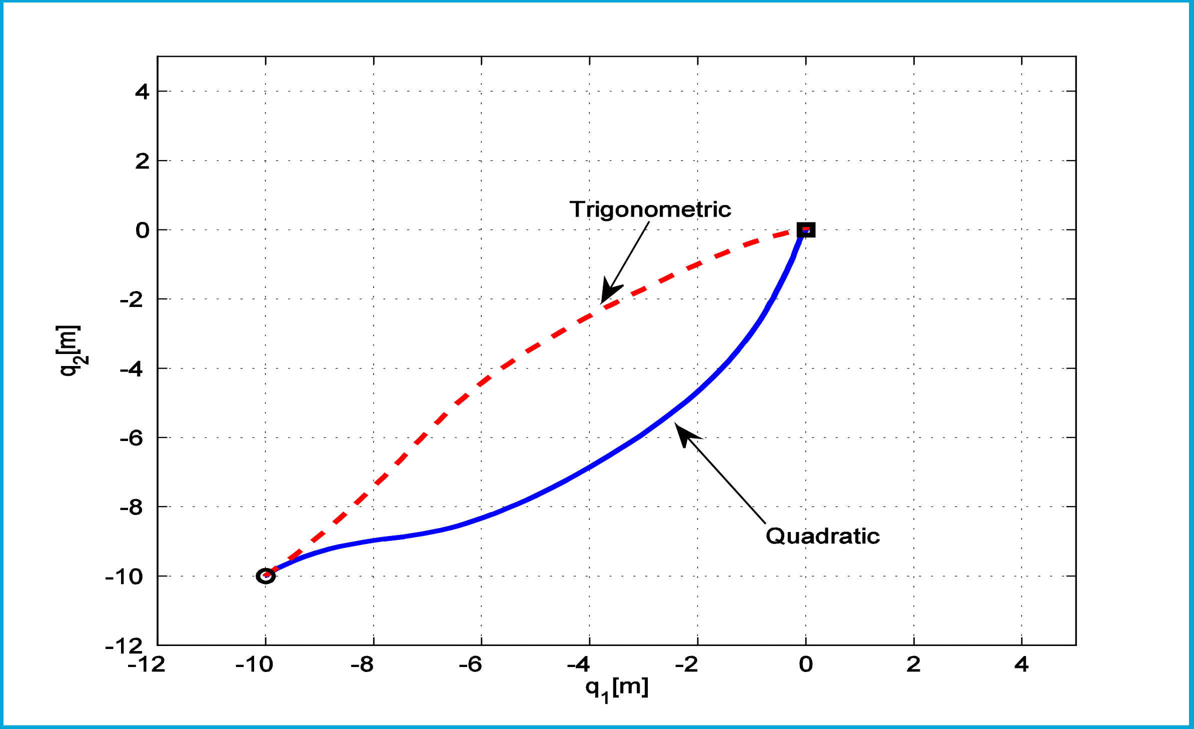

Figure 7. Ship position coordinates in the q1q2-plane,for the static quadratic controller (solid line) and the trigonometric controller (dashed line).

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Family of Passivity Based Controllers

3. Dynamic quadratic controller

A quadratic energy shaping

$$H_{de}(q,z,z_e)=\frac{1}{2}q^TKq+\frac{1}{2}z^TM^{-1}z+\frac{1}{2}z_e^TM^{-1}z_e \qquad (11)$$

$$\tau_{dq}=-K_pJ^T(q_3)Kq+K_Iz_e-K_D\,J^T(q_3)\,\dot{q}-J^T(q_3)b \qquad (12)$$

$$\dot{z}_e=-J^T(q_3)Kq \qquad (13)$$

A nonlinear output feedback PID-control law with a feed forward term

Family of Passivity Based Controllers

4. Dynamic trigonometric controller

A trigonometric energy shaping

$$H_{de}(q,z,z_e)=\frac{1}{2}q_{12}^T C_{12} q_{12}+c_3(1-\cos q_3)+\frac{1}{2}z^T M^{-1} z+\frac{1}{2}z_e^T M^{-1} z_e \qquad (15)$$

$$\tau_{dq}=-K_p J^T(q_3) C\begin{bmatrix} q_1 \\ q_2 \\ \sin q_3 \end{bmatrix}+K_I z_e-K_D J^T(q_3)\dot{q}-J^T(q_3) b \qquad (16)$$

$$\dot{z}_e=-J^T(q_3) C\begin{bmatrix} q_1 \\ q_2 \\ \sin q_3 \end{bmatrix} \qquad (17)$$

A nonlinear output feedback PID-control law with a feed forward term

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Family of Passivity Based Controllers

- Role of derivative term in control laws

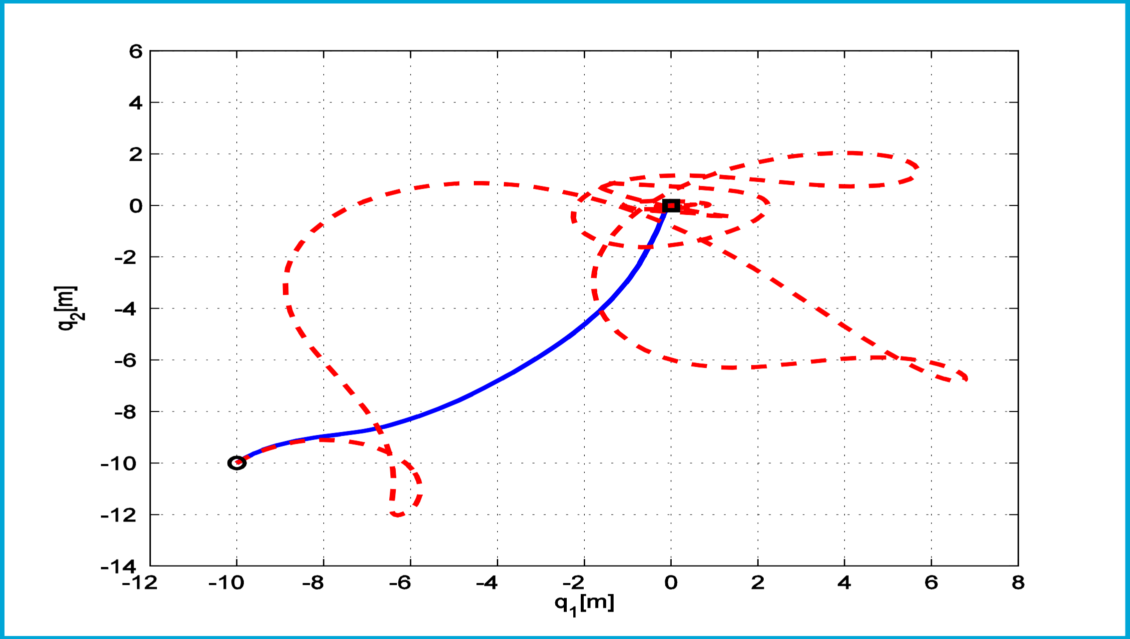

Figure 8. Ship position trajectories in the q1q2-plane, for the static quadratic controller with extra damping (solid line) and the original damping coefficient (dashed line).

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Family of Passivity Based Controllers

- Static vs dynamic controllers

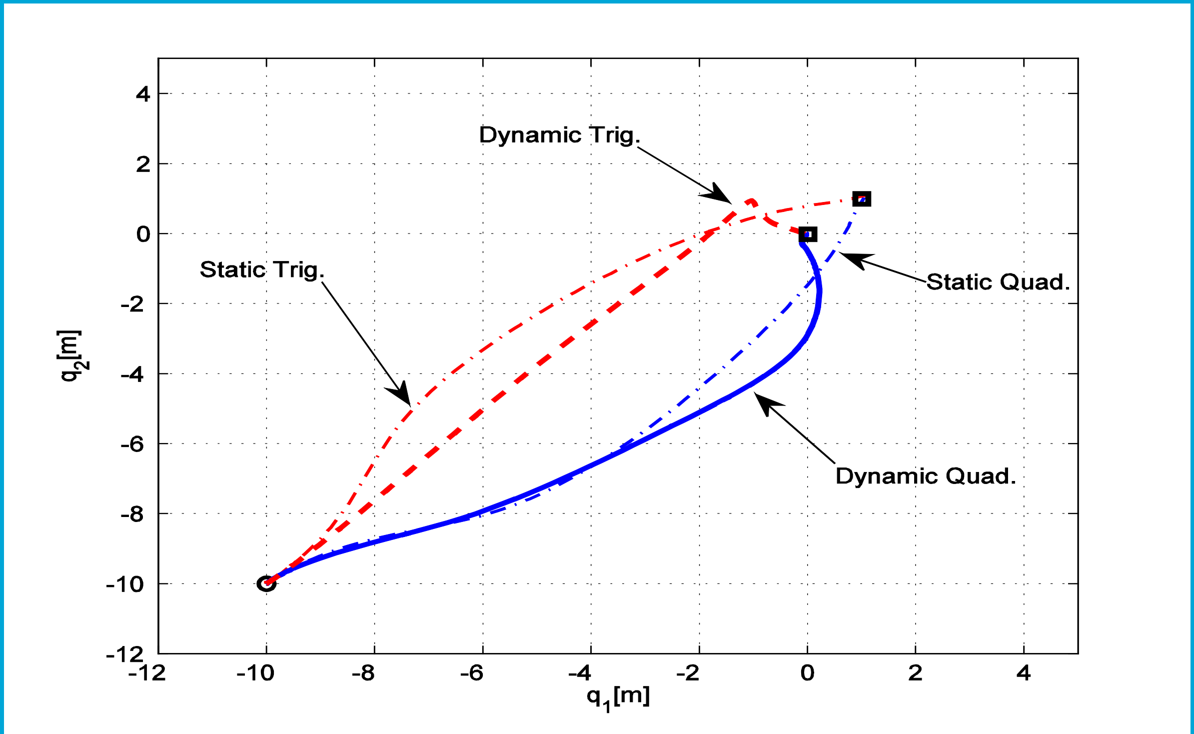

Figure 9. Ship position coordinates in the q1q2-plane,for the static (quadratic and trigonometric) controller (solid line) and the dynamic (quadratic and trigonometric) controller (dashed line).

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Summary and Conclusions

- Port-Hamiltonian methodology and IDA-PBC technique
- Dynamic positioning problem of a sea vessel in port-Hamiltonian structure
- A family of passivity based controllers with simulation results is presented
- Four main observations: (i) The controllers obtained are output feedback (ii) Heading angle can efficiently be controlled by using trigonometric energy shaping (iii) In the presence of disturbances , dynamic controller yields the desired performance (iv) The derivative term in controller equation increases the damping effect and results in a smooth trajectory .

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