CALZONI SPA

Applicazioni di controllo al moto di veicoli marini

ing. Daniele Bertin
Calzoni S.p.A.

Sommario

Lezione 1

- Introduzione: problemi di controllo, applicazioni
- Modellistica dei veicoli marini
- Autopiloti per navi: Introduzione

Lezione 2

- Posizionamento Dinamico per navi di superficie

CALZONI SPA

Veicoli marini

- Navi di superfice
  - navi dislocanti (bassa velocita')
  - navi plananti o semidislocanti (alta velocita')
  - navi dislocanti SWATH
  - navi a supporto idrodinamico (aliscafi, ….)
  - navi a effetto superfice (SES, WIG, …)

- Veicoli subaquei
  - ROV
  - AUV
  - Sommergibili

D. Bertin

Problemi di controllo per navi di superficie

- Problemi di navigazione/manovra
  - Tenuta di prora- Couse Keeping (Giropiloti o Autopiloti tradizionali)
  - Tenuta di Percorso - Track Keeping
  - Posizionamento dinamico - Dynamic Positioning

- Problemi di Tenuta al mare/Comfort - Seakeeping/Ride comfort
  - Smorzamento rollio (pinne, casse di compensazione, ..)
  - Smorzamento rollio con timone
  - Smorzamento moti (Ride Control Systems)

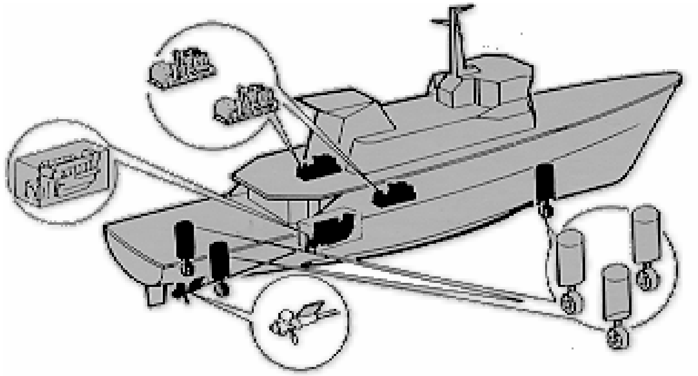
Problemi di controllo per veicoli subaquei

- Problemi di navigazione/manovra
  - Controllo della velocita’
  - Tenuta di prora- Couse Keeping (Giropiloti o Autopiloti tradizionali)
  - Tenuta di Percorso - Track Keeping
  - Posizionamento dinamico - Dynamic Positioning
  - Controllo di quota - Diving control
- Problemi di stabilizzazione
  - Smorzamento moti angolari

D. Bertin

Problemi di controllo della propulsione

- Allocazione delle spinte in diversi propulsori



- Controllo della spinta
  - legame comando-organo di attuazione
  - effetti idrodinamici della velocita’

Tecniche di controllo maggiormente utilizzate

- PID (giropiloti)
- LQG (autopiloti, RRS)
- Controllo adattativo (Gain Scheduling)
- Controllo Predittivo (autopiloti, abbandonato in diversi casi)
- Sliding modes (veicoli subaquei)
- $H\infty$ (RRS)
- Feedback Linearization, Backstepping (autopiloti)
- Altre (solo ricerca): Fuzzy, neurali, passivita', QFT

Modellistica dei sistemi marini: moti del veicolo

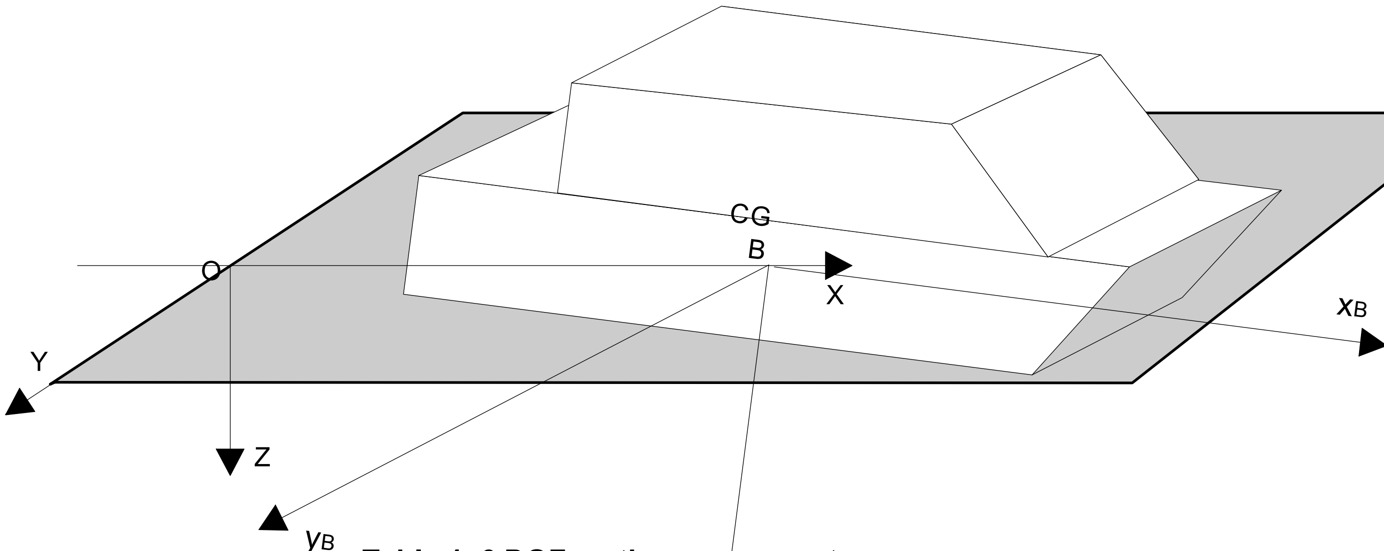


Table 1. 6 DOF motion components.

DOF	Motion (Body-fixed)	Vector components	Inertial position and Euler angles	Body-fixed velocities	Forces and moments
			η	ν	τ
1	surge	(linear)	x	u	X
2	sway		y	v	Y
3	heave		z	w	Z
4	roll	(angular)	ϕ	p	K
5	pitch		θ	q	M
6	yaw		ψ	r	N

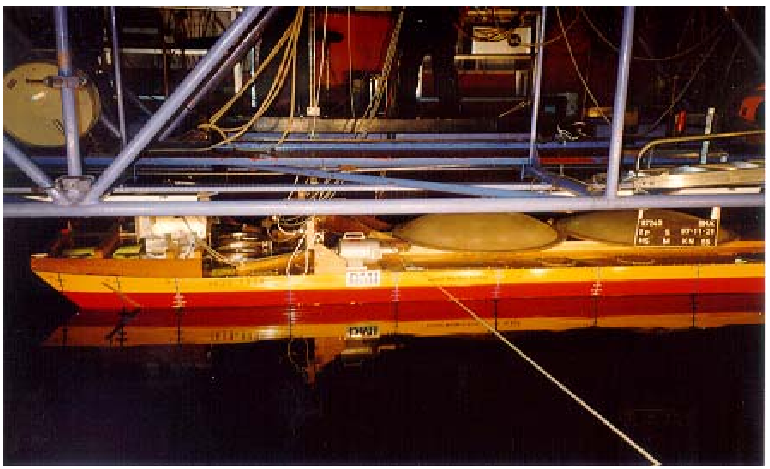
Denominazione dei moti

- avanzamento
- deriva
- sussulto
- rollio
- beccheggio
- imbardata

D. Bertin

Modellistica dei sistemi marini: tipi di modelli

- Modelli fisici
  - modelli in scala: similitudine geometrica, similitudine dinamica non possibile in pratica (Numeri di Froude e Reynolds)

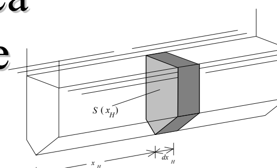


- Modelli matematici numerici
  - Equazioni della fluidomeccanica (in principio Navier-Stokes)
  - Equazioni della fluidomeccanica con approssimazioni numeriche (strip theory, 3D)
  - Equazioni della meccanica con approssimazioni sulla espressione delle forze:
    - modulari. Additivita' delle forze (sviluppo in serie di Taylor, spline, …)
    - olistici
  - Modelli comportamentali input-output: f.d.t. (identificazione Black-box)

$$X - \frac{1}{\rho}\frac{\partial p}{\partial x} = u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} + \frac{\partial u}{\partial t}$$

$$Y - \frac{1}{\rho}\frac{\partial p}{\partial y} = u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} + \frac{\partial v}{\partial t}$$

$$Z - \frac{1}{\rho}\frac{\partial p}{\partial z} = u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} + \frac{\partial w}{\partial t}$$



Complessita'

generalita'

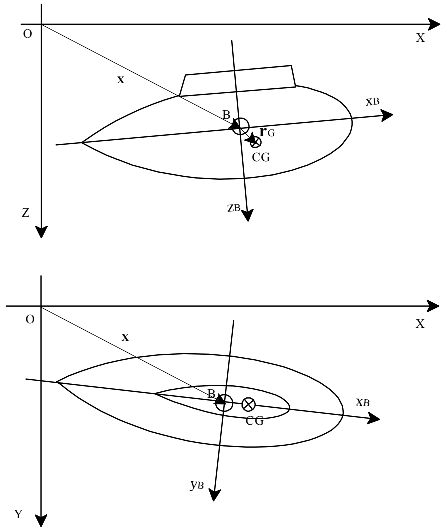
D. Bertin

Modellistica dei sistemi marini: il ruolo dei modelli

- I modelli possono avere diversi ruoli:
  - analisi e dimensionamento del processo da controllare (nave)
  - determinazione dei parametri di un modello matematico (modelli fisici)
  - progetto di un sistema di controllo (modelli semplificati)
  - simulazione per verifica del sistema di controllo

  - analisi manovrabilita' o tenuta al mare (progetto di navi)
  - simulazione per addestramento personale (simulatore come prodotto)

Modellistica dei sistemi marini: le equazioni costitutive



$$\mathbf{M}\dot{\mathbf{v}}+\mathbf{C}(\mathbf{v})\mathbf{v}=\boldsymbol{\tau}_g+\boldsymbol{\tau}_h(\dot{\mathbf{v}},\mathbf{v},\boldsymbol{\eta},waves,current,wind,\delta)$$

- A suitable model is expressed by the vector equation representing the momentum and the momentum of momentum conservation equation with respect to the body frame.

$$\dot{\boldsymbol{\eta}}=\mathbf{J}\mathbf{v}$$

$$\mathbf{M}_B\dot{\mathbf{v}}+\mathbf{C}_B(\mathbf{v})\mathbf{v}=\boldsymbol{\tau}_g+\boldsymbol{\tau}_h+\boldsymbol{\tau}_f+\boldsymbol{\tau}_R+\boldsymbol{\tau}_p+\boldsymbol{\tau}_c$$

where the force vectors τ are defined in the body frame and identified by the following subscripts:

- g gravitational
- h body hydrodynamics, ha added mass, hd damping
- f hydrofoils (lumped forces)
- R rudders and control surfaces (if any)
- p propulsion
- c cable
- w waves (in general)

D. Bertin

In generale il modello della dinamica parte dalle equazioni cardinali di conservazione della q.d.m. ad un riferimento fissato con il corpo rigido

$$\boldsymbol{\eta}=\begin{bmatrix}\eta_1\\\eta_2\\\eta_3\\\eta_4\\\eta_5\\\eta_6\end{bmatrix}=\begin{bmatrix}\mathbf{r}_G(\text{linear})\\\boldsymbol{\phi}_G(\text{angular})\end{bmatrix}=\begin{bmatrix}r_{G1}\\r_{G2}\\r_{G3}\\\phi_{G1}\\\phi_{G2}\\\phi_{G3}\end{bmatrix}\qquad \mathbf{v}=\begin{bmatrix}\nu_1\\\nu_2\\\nu_3\\\nu_4\\\nu_5\\\nu_6\end{bmatrix}=\begin{bmatrix}\mathbf{v}\\\boldsymbol{\omega}\end{bmatrix}=\begin{bmatrix}v_1\\v_2\\v_3\\\omega_1\\\omega_2\\\omega_3\end{bmatrix}\leftrightarrow\begin{bmatrix}u\\v\\w\\p\\q\\r\end{bmatrix}$$

Hydrodynamic forces

Typical hypotheses

- Superposition of effects of the force components
- Linearity property in the oscillatory hydrodynamic components: radiation, wave excitation
- The viscous effects of the waves are neglected.

D. Bertin

Table A. Classification of the hydrodynamic forces.

	Stationary	**Not stationary**	
		Reaction	**Excitation**
Potential flow	hydrostatic (R) wave resistance (R) added drag (D)	radiation (add.mass (I) and pot.damp (D))	wave excitation (F-K and diffraction) cushion hydrodynamic
Viscous flow	friction (D) viscous pressure (D)		

Forze idrodinamiche “potenziali”

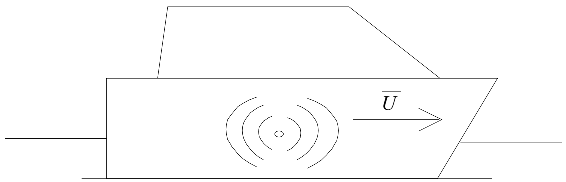
Not stationary components of the Potential forces: fundamental decomposition

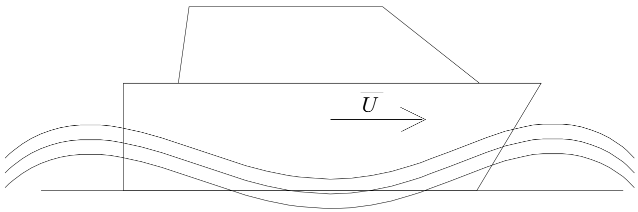
The generalised hydrodynamic resultant is so composed by

$$\tau_h = \tau_{hr} + \tau_{hm} + \tau_{hs} + \tau_{he} + \tau_{hw} + \tau_{hv}$$

with the following meaning for the subscripts

hr	radiation forces
hm	wave resistance of the hull (wave-making)
hs	hydrostatic (buoyancy)
he	wave excitation force
hw	wave added drag
hv	viscous forces = friction+viscous pressure





Forze idrodinamiche di radiazione

Radiation forces: added mass+damping

- The **added mass** term is constituted by

$$\boldsymbol{\tau}_{hrA} = -\mathbf{A}_{hr}(\omega)\ddot{\boldsymbol{\eta}}$$

where

$$\mathbf{A}_{hr}(\omega) = -\begin{bmatrix} X_{\dot{u}} & X_{w} & X_{p} & X_{q} \\ Z_{\dot{u}} & Z_{w} & Z_{p} & Z_{q} \\ K_{\dot{u}} & K_{w} & K_{p} & K_{q} \\ M_{\dot{u}} & M_{w} & M_{p} & M_{q} \end{bmatrix} = \left\{A_{ij}(\omega)\right\}$$

- The **potential damping** term is:

$$\boldsymbol{\tau}_{hrB} = -\mathbf{B}_{hr}(\omega)\dot{\boldsymbol{\eta}}$$

with

$$\mathbf{B}_{hr}(\omega) = \left\{B_{ij}(\omega)\right\} = \begin{bmatrix} B_{11} & 0 & 0 & 0 \\ 0 & B_{33} & 0 & B_{35} \\ 0 & 0 & B_{44} & 0 \\ 0 & B_{53} & 0 & B_{55} \end{bmatrix}$$

where only the significant terms B_{ij} are indicated.

A_{ij} B_{ij} are the coefficients often determined by the strip-theory

Modellistica dei sistemi marini: un modello a 6 DOF

$$\mathbf{M}=\begin{bmatrix} m-X_{\dot u} & 0 & 0 & 0 & mz_G & 0 \\ 0 & m-Y_{\dot v} & 0 & -mz_G & 0 & mx_G \\ 0 & 0 & m-Z_{\dot w} & 0 & -mx_G & 0 \\ 0 & -mz_G & 0 & I_x-K_{\dot p} & 0 & -I_{xz} \\ mz_G & 0 & -mx_G & 0 & I_y-M_{\dot q} & 0 \\ 0 & mx_G & 0 & -I_{zx} & 0 & I_z-N_{\dot r} \end{bmatrix}$$

$$\dot{\eta}=\mathbf{J}(\eta)\nu_r+\nu_{c0}$$
$$\mathbf{M}\dot{\nu}_r=-\mathbf{C}(\nu_r)\nu_r-\mathbf{D}(\nu_r)\nu_r-\mathbf{g}(\eta)+\tau_f+\tau_r+\tau_p+\tau_c$$

$$\mathbf{C}(\nu)=\begin{bmatrix} 0 & 0 & 0 & mz_G r & -mx_G q+m_{33}w & -mx_G r-m_{22}v \\ 0 & 0 & 0 & -m_{33}w & m(z_G r+x_G p) & m_{11}u \\ 0 & 0 & 0 & -mz_G p+m_{22}v & -mz_G q-m_{11}u & mx_G p \\ -mz_G r & m_{33}w & mz_G p-m_{22}v & 0 & -I_{xz}p+m_{T66}r & -m_{55}q \\ mx_G q-m_{33}w & -m(z_G r+x_G p) & mz_G q+m_{11}u & I_{xz}p-m_{66}r & 0 & -I_{xz}r+m_{44}p \\ mx_G r+m_{22}v & -m_{11}u & -mx_G p & m_{55}q & I_{xz}r-m_{44}p & 0 \end{bmatrix}$$

with the additional outputs

$$\nu=\nu_r+\nu_c=\nu_r+\mathbf{J}^{-1}(\eta)\nu_{c0}$$

$$\mathbf{D}(\nu)=-\begin{bmatrix} X_u+X_{uu}|u| & 0 & 0 & 0 & 0 & X_{vr}v \\ 0 & Y_{uv}u_0+Y_{wv}w_0+Y_{vv}|v| & 0 & 0 & 0 & Y_{ur}u+Y_{rr}|r| \\ 0 & 0 & Z_{uw}u_0+Z_{vw}v_0+Z_{ww}|w| & 0 & Z_{uq}u & 0 \\ 0 & K_{vv}|v| & 0 & K_{up}u_0+K_{pp}|p| & 0 & 0 \\ 0 & 0 & M_{uw}u+M_{ww}|w| & 0 & M_{uq}u_0+M_{qq}|q| & 0 \\ 0 & N_{uv}u+N_{vv}|v| & 0 & 0 & 0 & N_{ur}u_0+N_{rr}|r| \end{bmatrix}$$

$$\dot{\nu}=\dot{\nu}_r+\frac{d\mathbf{J}^{-1}(\eta(t))}{dt}\nu_{c0}$$

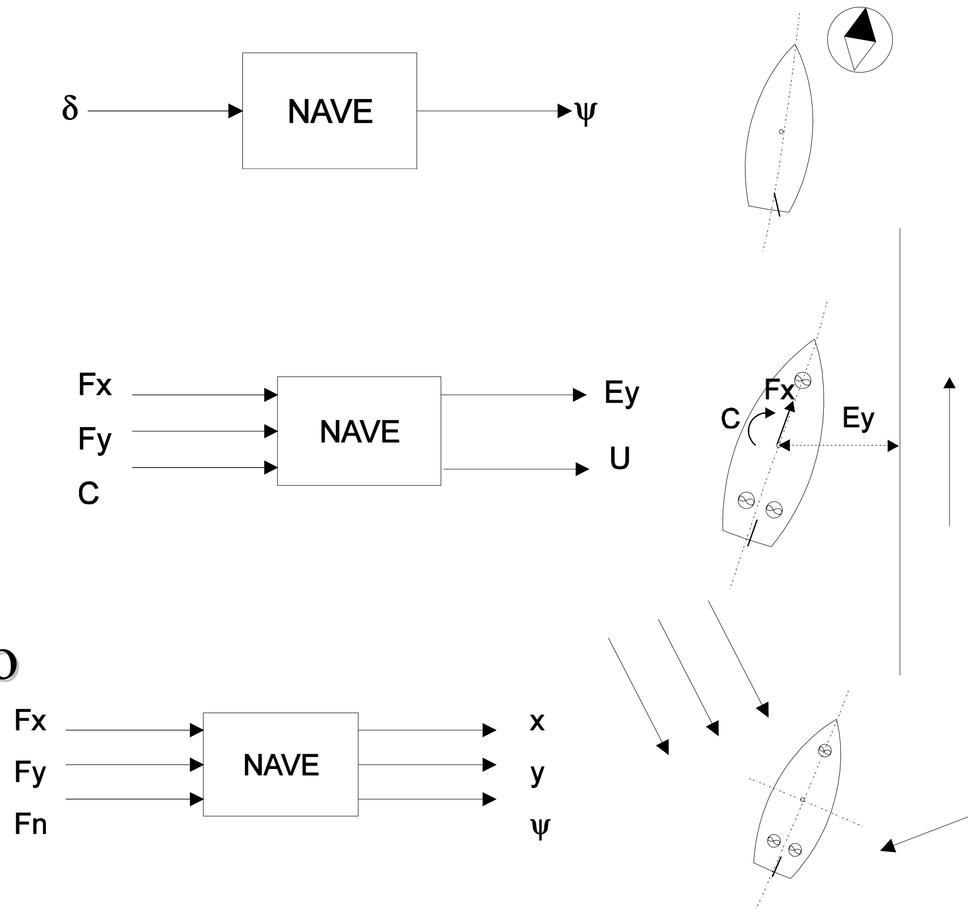
$$\nu_{c0}=\begin{bmatrix}u_{c0} & v_{c0} & 0 & 0 & 0 & 0\end{bmatrix}^T$$

inertial referenced water current (input data)

$$\mathbf{g}(\eta_2)=\begin{bmatrix} (W_B-B_B)s\theta \\ -(W_B-B_B)c\theta s\phi \\ -(W_B-B_B)c\theta c\phi \\ (z_G W_B-z_B B_B)c\theta s\phi \\ (z_G W_B-z_B B_B)s\theta+(x_G W_B-x_B B_B)c\theta c\phi \\ -(x_G W_B-x_B B_B)c\theta s\phi \end{bmatrix}$$

Autopiloti per navi: Introduzione

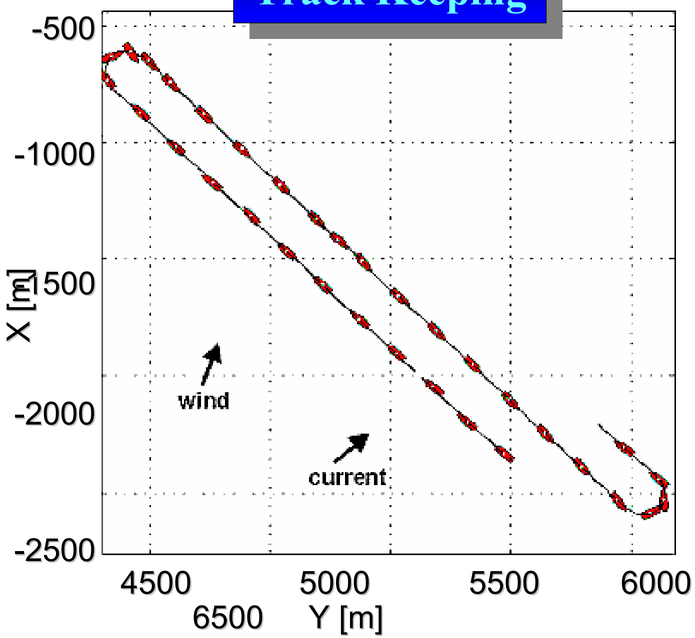
- Giropiloti
  - Controllo della prora nave
- Transito su percorso
  - Controllo su percorso (scostamento)
- Sistemi di Posizionamento Dinamico
  - Controllo della posizione e prora (bassa velocita')

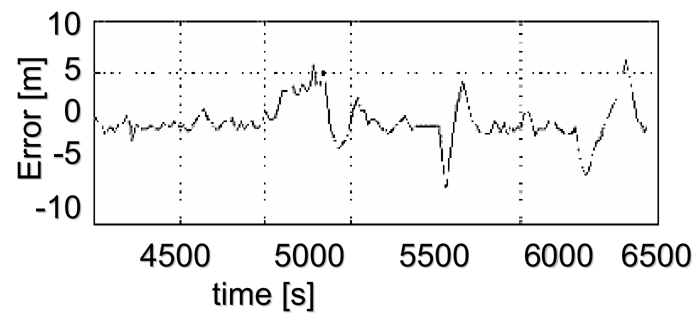


D. Bertin

Autopilota di Tenuta di Percorso

Track Keeping



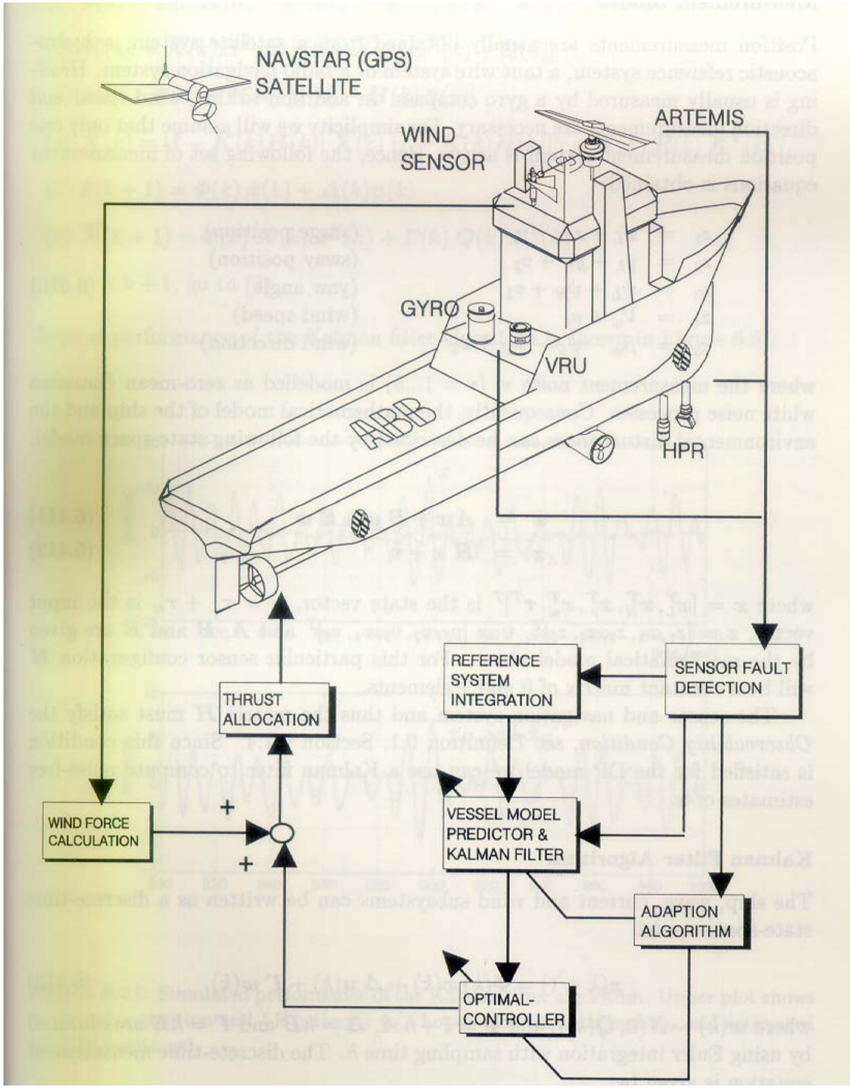


D. Bertin

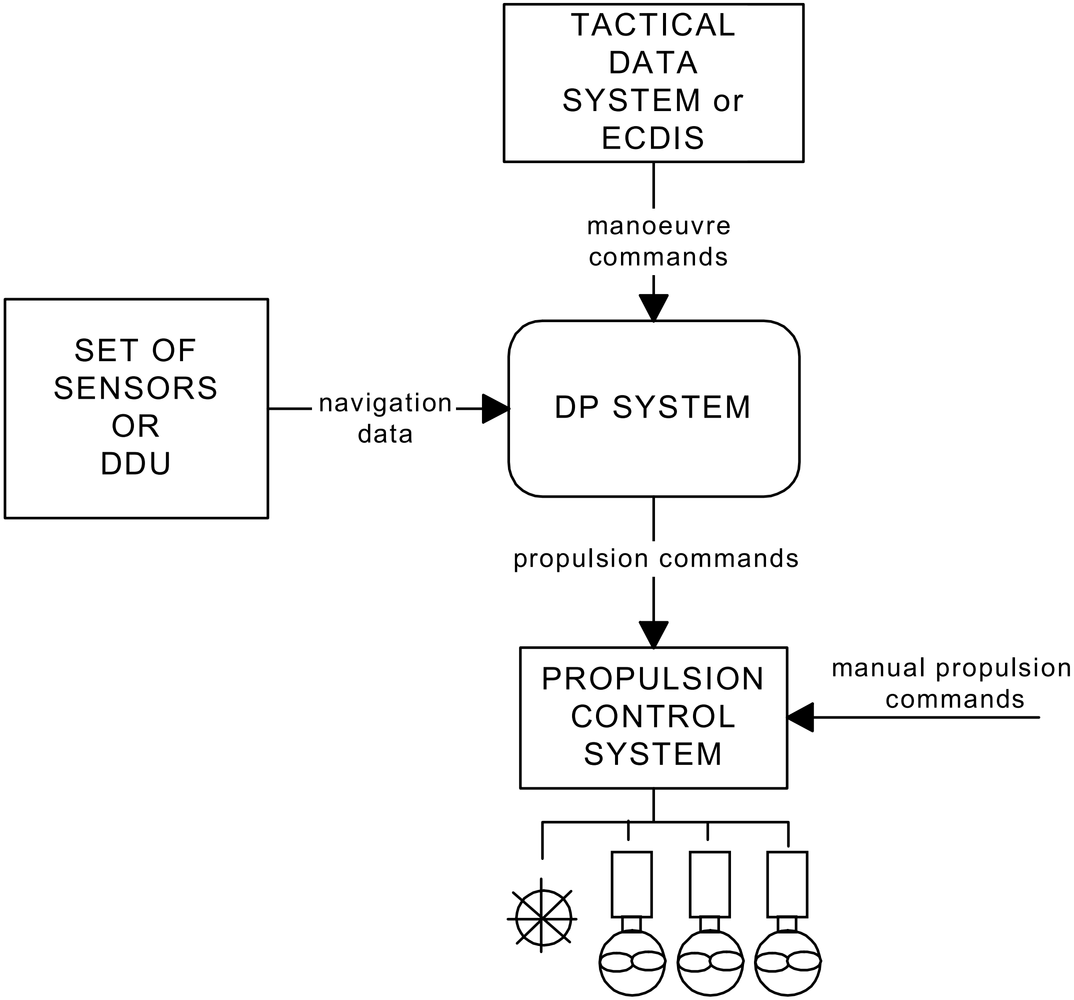
POSIZIONAMENTO DINAMICO PER NAVI DI SUPERFICE

Un Sistema di Posizionamento Dinamico (DP) comprende le seguenti parti principali:

- Acquisizione e condizionamento dati da sensori (GPS)
- Stimatore: ricostruzione e filtraggio
- Regolatore DP
- Compensazione diretta perturbazioni ambientali (wind force)
- Comando Coordinato dei propulsori (Thrust allocation)



Contesto di un sistema di DP

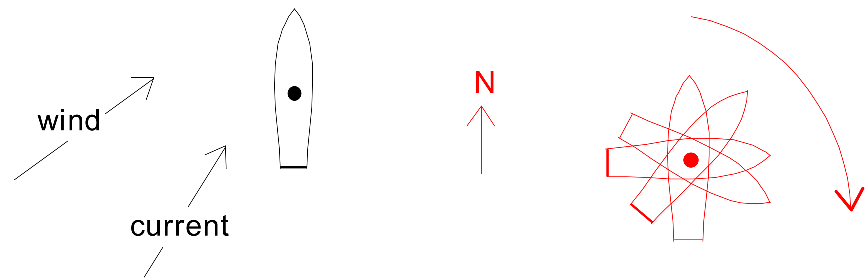


Manovre principali

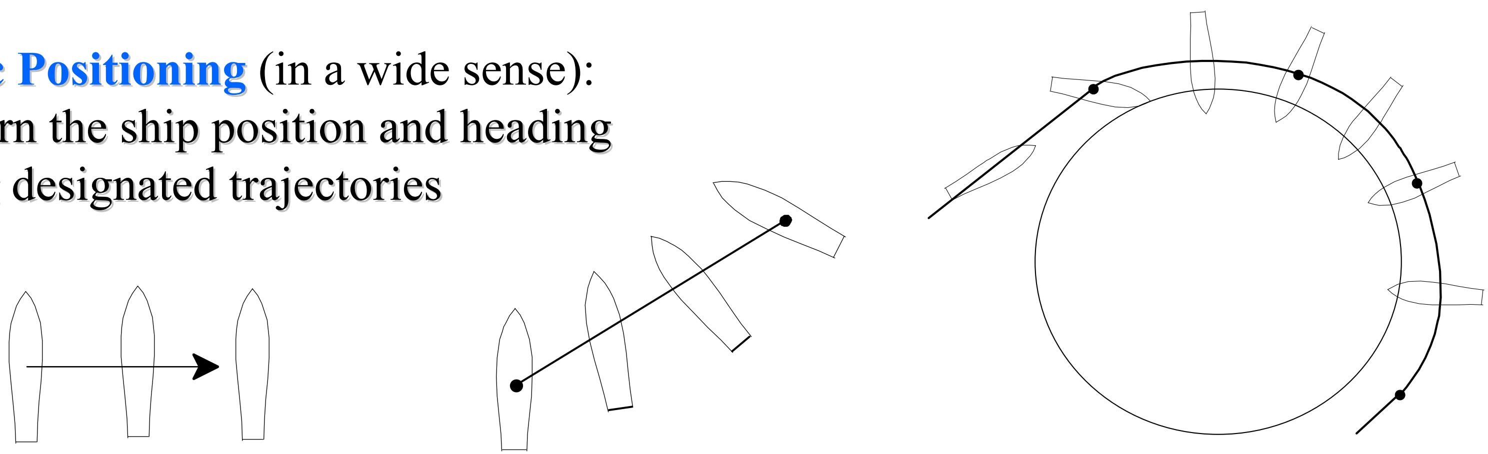
Definition (DP system): control system to maintain the ship position exclusively by means of active thrusters.

In a wide sense the set of manoeuvres can be grouped in the following basic types:

Hovering: control of position and heading



Dynamic Positioning (in a wide sense): Govern the ship position and heading along designated trajectories



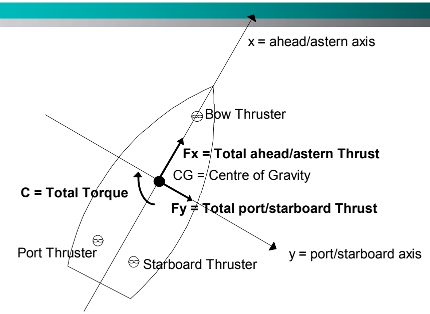
D. Bertin

Comando coordinato della propulsione

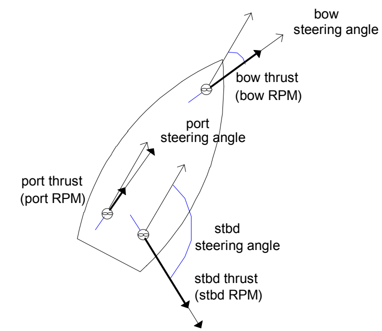
D. Bertin

Criteria for the propulsion coordination

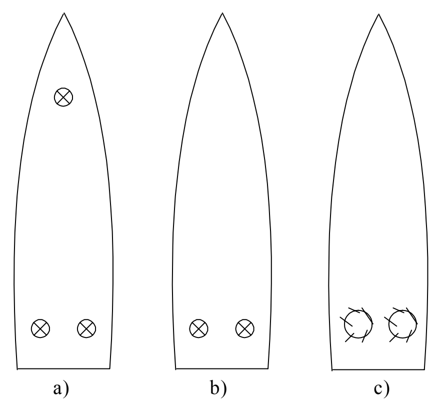
- optimal or valid, power consumption with respect to the infinite solution available to apply a total force and moment
- nullify or minimise the interference among the thruster jets
- reduce the individual thruster operational state (rpm, bearing) frequency and rate of changes
- avoid the interference of the thruster jets with special devices (sonar, log Doppler)
- handle different configuration of the propulsion system due to voluntary change or faults
- take into account the cavitation phenomena
- take into account the hydrodynamic influence, hull and water relative speed, on the thruster applied force.



Total Thrust and Torque



Single Thruster RPM and Steering angle



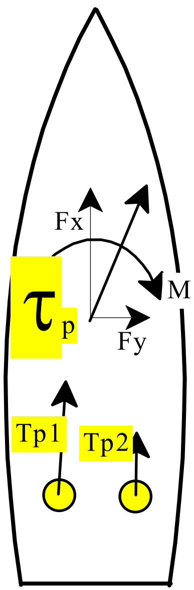
Propulsion configuration for

a) Lerici, Gaeta, Huon classe azimuth thrusters;

b) Mahamiru class, azimuth thrusters ;

c) Osprey class, VSP;

Comando coordinato della propulsione: soluzione diretta



$$\tau_p = \begin{bmatrix} F_x \\ F_y \\ M \end{bmatrix}$$

where :

$$\mathbf{T_p} = \begin{bmatrix} \mathbf{T_{p1}} \\ \mathbf{T_{p2}} \end{bmatrix} \begin{bmatrix} T_{p1x} \\ T_{p1y} \\ T_{p2x} \\ T_{p2y} \end{bmatrix}$$

τ_p= $\mathbf{B_p}$ $\mathbf{T_p}$ from mechanics

$\mathbf{T_p}$= $\mathbf{B_p}^+$ τ_p is the allocation law

$\mathbf{B_p}^+$ is obtained solving an optimization problem as the pseudoinverse of $\mathbf{B_p}$.

Assumed:

Ds distance of the thrusters from the ship center (along x axis>0).

Dst distance between the thrusters

$$Bp = \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \\ Dst & -Ds & -Dst & -Ds \end{bmatrix}$$

Bp^+ = Bp'inv(Bp Bp')=

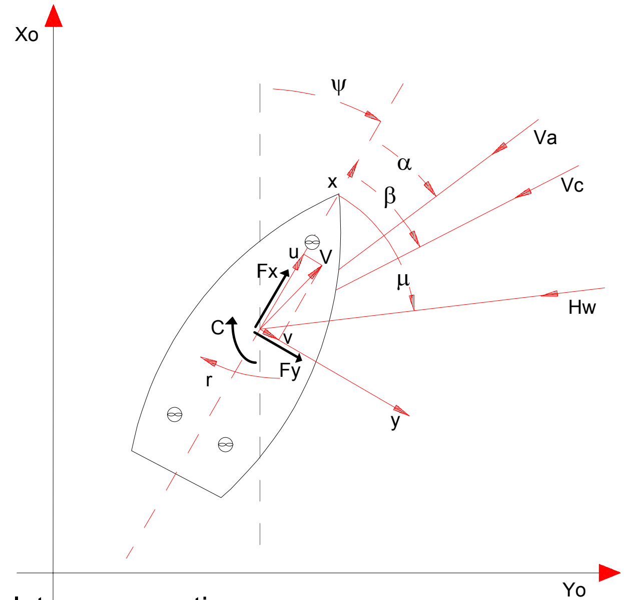
$$\begin{bmatrix} 1/2 & 1/2\ Ds/Dst & 1/(2\ Dst) \\ 0 & 1/2 & 0 \\ 1/2 & -1/2\ Ds/Dst & -1/(2\ Dst) \\ 0 & 1/2 & 0 \end{bmatrix}$$

D. Bertin

Modello matematico: cinematica

D. Bertin

The relationship between the absolute and dynamic coordinates velocities is given by:



$$\dot{\eta} = \mathbf{J}(\eta)\nu$$

where

$$\eta = \begin{bmatrix} \eta_1 \\ \eta_2 \\ \eta_6 \end{bmatrix} = \begin{bmatrix} X \\ Y \\ \Psi \end{bmatrix}; \nu = \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_6 \end{bmatrix} = \begin{bmatrix} u \\ v \\ r \end{bmatrix}$$

result

$$\mathbf{J}(\eta) = \begin{bmatrix} c\eta_6 & -s\eta_6 & 0 \\ s\eta_6 & c\eta_6 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

In order to reduce the length of the expressions the following nomenclature conventions are made:

s $\leftrightarrow$ sin(.); c $\leftrightarrow$ cos(.); t $\leftrightarrow$ tan(.)

Modello matematico: dinamica

$$\dot{\eta} = \mathbf{J}(\eta)\nu$$

$$\mathbf{J}(\eta) = \begin{bmatrix} c\eta_6 & -s\eta_6 & 0 \\ s\eta_6 & c\eta_6 & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\boxed{\mathbf{M}_T\dot{\nu} = [-\mathbf{C}_T(\nu) + \mathbf{D}_H(\nu)]\nu + \tau_r + \tau_a + \tau_w + \tau_p}$$

where

$$\mathbf{M}_\mathrm{T} = \mathbf{M}_\mathrm{B} + \mathbf{M}_\mathrm{A} = \begin{bmatrix} \mathrm{m} + \mathrm{m}_{\mathrm{A}1} & 0 & 0 \\ 0 & \mathrm{m} + \mathrm{m}_{\mathrm{A}2} & 0 \\ 0 & 0 & \mathrm{I}_{33} + \mathrm{I}_{\mathrm{A}3} \end{bmatrix} = \begin{bmatrix} \mathrm{m}_{\mathrm{T}1} & 0 & 0 \\ 0 & \mathrm{m}_{\mathrm{T}2} & 0 \\ 0 & 0 & \mathrm{I}_{\mathrm{T}3} \end{bmatrix}$$

$$\mathbf{C}_\mathrm{T}(\nu) = \mathbf{C}_\mathrm{B}(\nu) + \mathbf{C}_\mathrm{A}(\nu) = \begin{bmatrix} 0 & 0 & -\mathrm{m}_{\mathrm{T}2}\nu_2 \\ 0 & 0 & \mathrm{m}_{\mathrm{T}1}\nu_1 \\ \mathrm{m}_{\mathrm{T}2}\nu_2 & -\mathrm{m}_{\mathrm{T}1}\nu_1 & 0 \end{bmatrix}.$$

$$\mathbf{D}_H = -\begin{bmatrix} X_u & 0 & 0 \\ 0 & Y_v & 0 \\ 0 & 0 & N_r \end{bmatrix}$$

Ipotesi fondamentali sul modello per la sintesi del controllore

- Piccole rotazioni di prora. Matrice di rotazione **J**=**I**. Misure di posizione e prora devono essere trasformate nel riferimento B.
- Disaccoppiamento degli assi (Piccole velocita' di rotazione: C≈0)
- Piccole velocita' (linearizzazione matrice D_H). Regime laminare
- velocita' nulla della corrente (preliminarmente)
- Dinamica degli attuatori semplificata (lineare)

$$\dot{\mathbf{x}} = \mathbf{A}_c\mathbf{x}_c + \mathbf{B}_c\mathbf{u}$$

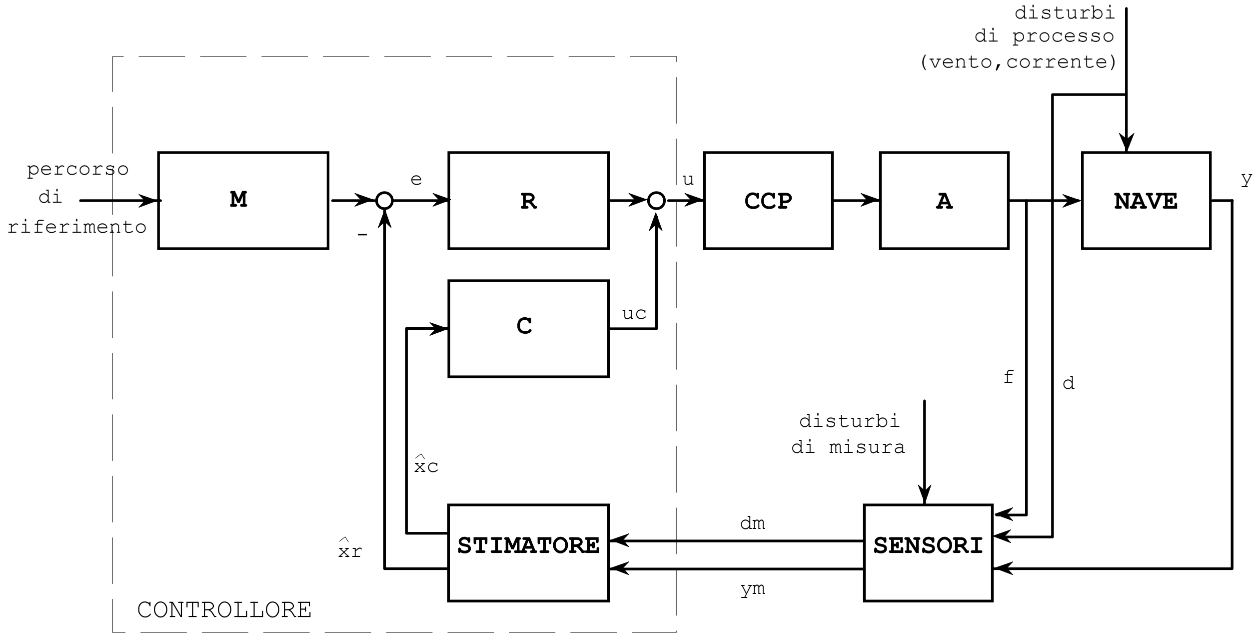
$$\mathbf{x}_c = \begin{bmatrix} \eta_B \\ \nu \\ \tau_p \end{bmatrix}; \mathbf{A}_c = \begin{bmatrix} 0 & \mathbf{I} & 0 \\ 0 & \mathbf{M}_T^{-1}\mathbf{D}_{H1} & \mathbf{M}_T^{-1} \\ 0 & 0 & -\mathbf{A}_p \end{bmatrix}; \mathbf{B}_c = \begin{bmatrix} 0 \\ 0 \\ \mathbf{A}_p \end{bmatrix}$$

$$\mathbf{A}_p = \begin{bmatrix} a_{p1} & 0 & 0 \\ 0 & a_{p1} & 0 \\ 0 & 0 & a_{p1} \end{bmatrix}$$

A meno dell'effetto onde e del processo di misura

Scelte di progetto del controllore

- sistema di controllo digitale diretto
- adozione del punto di vista digitale
- impostazione moderna (LQ)
- descrizione stocastica dei disturbi di processo e di misura
- sistema di controllo a 2 gradi di liberta'



Regolatore

Continuos time model

$$\dot{\mathbf{x}}_R = \mathbf{A}_{Rc}\mathbf{x}_{Rc} + \mathbf{B}_{Rc}\mathbf{u}_R$$

$$\mathbf{x}_{Rc} = \begin{bmatrix} \eta_B \\ \nu \\ \tau_p \end{bmatrix}; \mathbf{A}_{Rc} = \begin{bmatrix} 0 & \mathbf{I} & 0 \\ 0 & \mathbf{M}_T^{-1}\mathbf{D}_{H1} & \mathbf{M}_T^{-1} \\ 0 & 0 & -\mathbf{A}_p \end{bmatrix}; \mathbf{B}_{Rc} = \begin{bmatrix} 0 \\ 0 \\ \mathbf{A}_p \end{bmatrix}$$

$$\mathbf{A}_p = \begin{bmatrix} a_{p1} & 0 & 0 \\ 0 & a_{p1} & 0 \\ 0 & 0 & a_{p1} \end{bmatrix}$$

The optimal LQ regulator associated to this model give a steady state error

In this basic formulation the three DOF are decoupled

The following criteria for LQ optimal design is used.

$$\mathrm{J} = \sum\left[\mathrm{x}_\mathrm{R}^\mathrm{T}\mathrm{Q}\mathrm{x}_\mathrm{R} + \mathrm{u}_\mathrm{R}^\mathrm{T}\mathrm{R}\mathrm{u}_\mathrm{R}\right]$$

leading to the control law

$$\mathbf{u}_\mathbf{R} = -\mathbf{K}_\mathbf{R}\mathbf{x}_\mathbf{R}$$

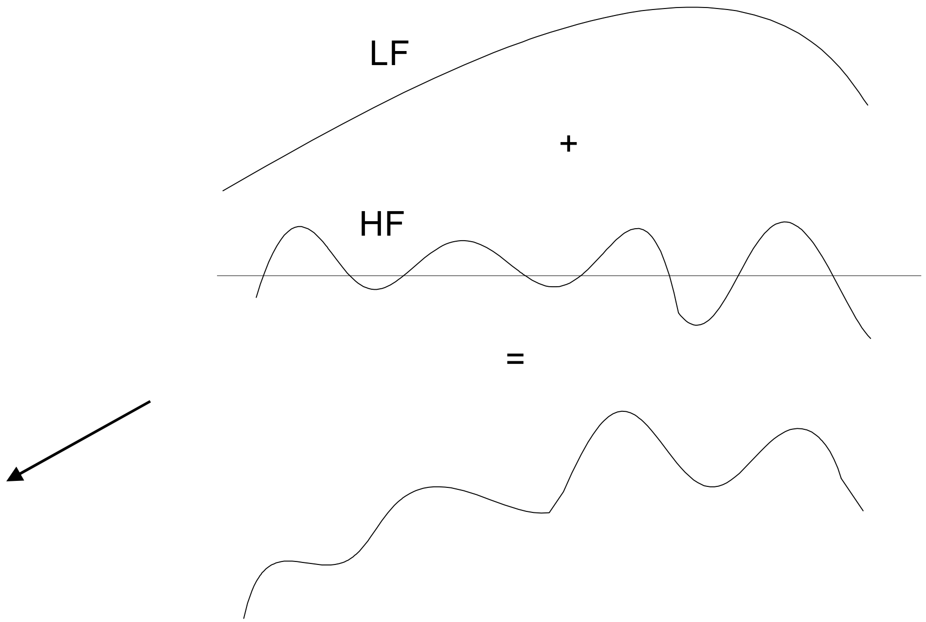
Sullo stimatore

Lo stimatore è costituito da un Filtro di Kalman il cui ruolo è il seguente:

- ricostruzione delle variabili di stato e filtraggio dei disturbi di misura
- "frequency-shaping" del controllore per evitare oscillazione onde (filtraggio degli effetti delle onde del primo ordine)
- stima di componenti di forza residue non misurate (corrente marina, errori di modello)
- gestione di casi degradati (senza parte o tutte le misure)

Errori nel modello di riferimento

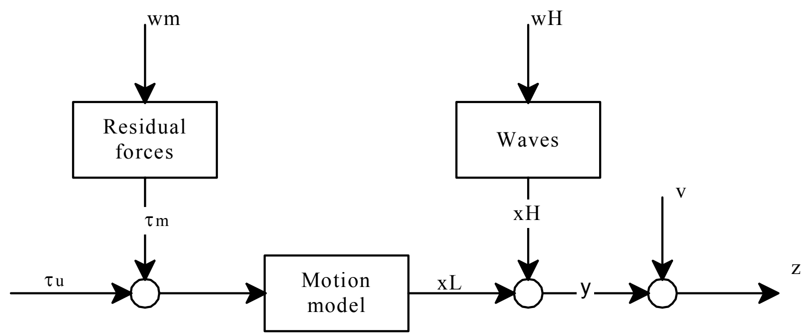
- Errori di modello
  - forze di attuazione e idrodinamiche (residue)
- Errori di misura
  - Onde (considerate come)
  - istantaneo sulla misura di posizione e velocita' (WGN)



Kalman Filter design

$$\mathbf{x}_L = \begin{bmatrix} \eta_B \\ \nu \\ \tau_m \end{bmatrix};$$

$$\tau_u = \tau_a + \tau_p$$



Reference model for the KF.

For DP

$$\dot{\mathbf{x}} = \begin{bmatrix} \dot{\eta}_L \\ \dot{\nu} \\ \dot{\tau}_m \\ \dot{\mathbf{x}}_H \end{bmatrix} = \begin{bmatrix} \mathbf{J}(\psi)\nu \\ \mathbf{M}^{-1}\left(-\mathbf{D}_\mathbf{T}(\nu_r)\nu_r + \mathbf{J}^T(\psi)\tau_m + \tau_u\right) + \mathbf{J}_d^T(\psi) r \nu_{c0} \\ -\mathbf{H}_c(\psi)\tau_m \\ \mathbf{A}_{\mathbf{Hc}} \end{bmatrix} + \left[\begin{array}{cc:c} \mathbf{0} & \mathbf{0} & \mathbf{0} \\ \mathbf{M}^{-1} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{J}(\psi) & \mathbf{0} \\ \hdashline \mathbf{0} & \mathbf{0} & \mathbf{G}_{\mathbf{Hc}} \end{array}\right] \mathbf{w}$$

$$\mathbf{x}_H = \begin{bmatrix} \xi \\ \eta_{BH} \end{bmatrix}; \mathbf{A}_{Hc} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\omega_0^2\mathbf{I} & -2\zeta\omega_0\mathbf{I} \end{bmatrix}; \mathbf{G}_{Hc} = \begin{bmatrix} \mathbf{0} \\ \mathbf{I}\omega_0 \end{bmatrix} \qquad (1)$$

$$\mathbf{y} = [\mathbf{C}_\mathbf{L} \quad \mathbf{C}_\mathbf{H}]\mathbf{x} + \mathbf{v}$$

$$\mathbf{y} = \begin{bmatrix} \eta \\ \nu \end{bmatrix}; \mathbf{C}_\mathbf{L} = \begin{bmatrix} \mathbf{J}^\mathbf{T} & \mathbf{0} & \mathbf{0} \\ \mathbf{0} & \mathbf{I} & \mathbf{0} \end{bmatrix}; \mathbf{C}_H = \begin{bmatrix} \mathbf{0} & \mathbf{J}^\mathbf{T} \\ \mathbf{0} & \mathbf{0} \end{bmatrix}; \qquad (2)$$

Modello HF (onde)

1.1.1.1 HF model

- **Continuos time**

The HF model keeps into account the high frequency motion (seen as a position disturbance.

$$\eta_{BH}(s) = \frac{K_H s}{s^2 + 2\zeta\omega_0 s + \omega_0^2} w_H$$

$K_H = \omega_0$ to have the same maximum of the response.

The realisation is

$$\dot{\hat{\mathbf{x}}}_H = \mathbf{A}_{cH}\hat{\mathbf{x}}_H + \mathbf{G}_{cH}\mathbf{w}_H$$

$$\hat{\mathbf{y}}_{\mathbf{H}} = \mathbf{C}_{\mathbf{Hy}}\hat{\mathbf{x}}_H$$

$$\hat{\mathbf{x}}_H = \begin{bmatrix} \hat{\xi} \\ \hat{\eta}_H \end{bmatrix}; \mathbf{A}_{cH} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\omega_0^2\mathbf{I} & -2\zeta\omega_0\mathbf{I} \end{bmatrix}; \mathbf{G}_{cH} = \begin{bmatrix} 0 \\ \mathbf{I}\omega_0 \end{bmatrix} \text{Discrete time}$$

$$\hat{\mathbf{y}}_{\mathbf{H}} = \hat{\eta}_H; \quad \mathbf{C}_{\mathbf{Hy}} = \begin{bmatrix} \mathbf{0} & \mathbf{C}_{\mathbf{H}\eta} \end{bmatrix}$$

D. Bertin

Applicazioni di DP

Lerici Class MHC

Hull: Intermarine
Length overall: 49,9 m
Displacement: 520 t
Propulsion: 3 azimuthing Calzoni thrusters

first commissioned in 1982

Gaeta Class MHC

Hull: Intermarine
Length overall: 52,5 m
Displacement: 697 t
Propulsion: 3 azimuthing Calzoni thrusters

first commissioned in 1992

Huon Class MHC

Hull: Intermarine
Length overall: 52,5 m
Displacement: 722 t
Propulsion: 3 azimuthing Calzoni thrusters

first commissioned in 1999

Osprey Class MHC

Hull: Intermarine
Length overall: 53,1 m
Displacement: 783 t
Propulsion: 2 aft Voith-Schneider

first tested in 1999

D. Bertin

Prove in mare

Hovering

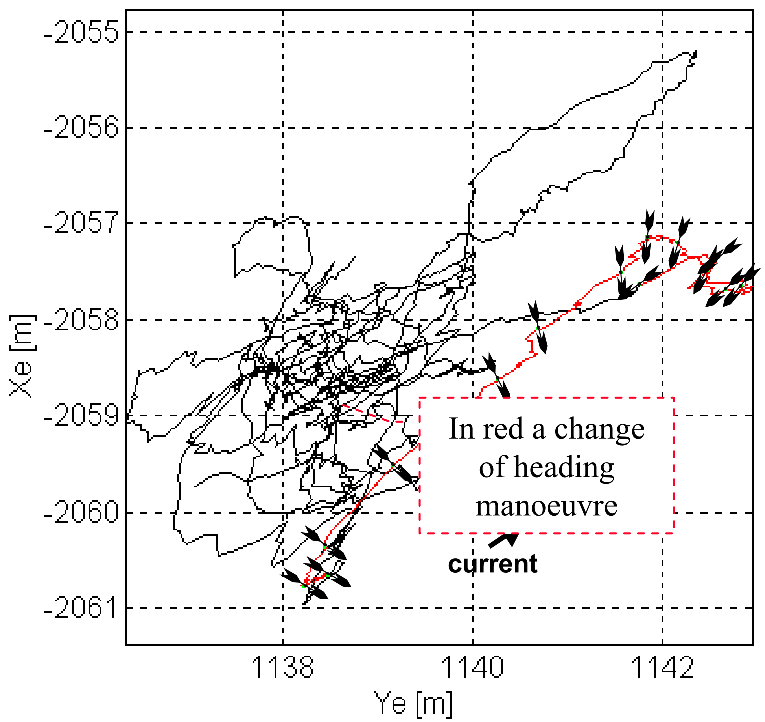
DYNAMIC POSITIONING - SEA TRIAL MHC "LERICI" (15/4/92)

STATION KEEPING WITH ROTATION

EXPERIMENT DATA:

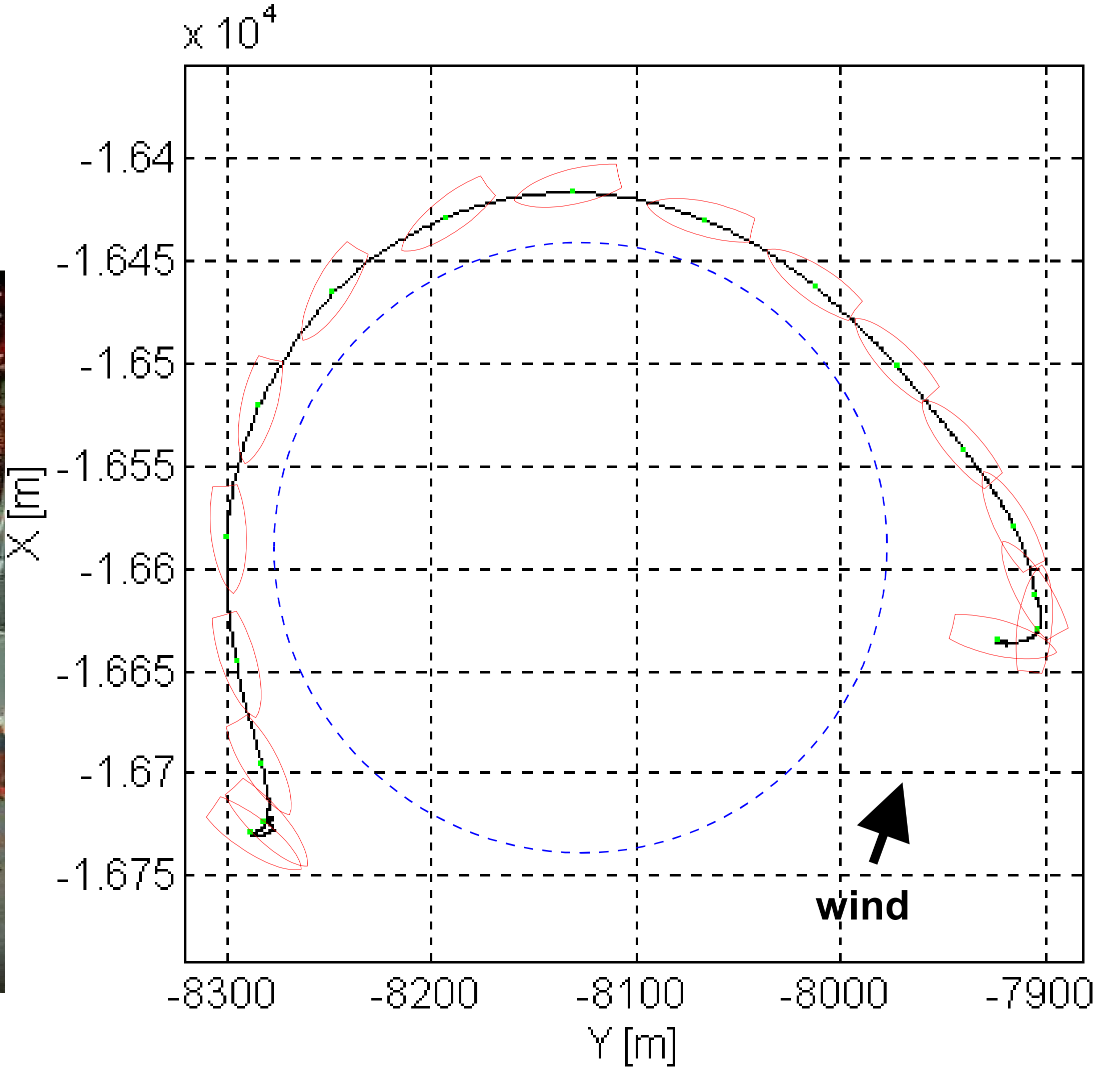
- **time period = 30 min**
- **initial heading 120°**
- **final heading 240°**
- **calm water**
- **wind: 8 kts (mean) with gusts**
- **current: 1.4 kts**

ship heading indicated during the rotation manoeuvre only



Prove in mare

Contact circling



D. Bertin