SHIP VOYAGE OPTIMISATION BY 3D DYNAMIC PROGRAMMING

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Università degli Studi di Genova
Italy

with the collaboration of Ennio Ottaviani
OnAir Srl, Genova, Italy
Background : emission reduction


• IMO EEOI should enter into force

• OBJECTIVES
  • monitor, report and verify CO2 emissions from ships as the first step of a staged approach to reduce greenhouse gas emissions
  • promote the reduction of CO2 emissions from maritime transport in a cost effective manner
Background: improve operational capacity

- Optimise fuel consumption
- Improve comfort on board
- Improve crew behavior and effectiveness
Decision support systems

- energy optimisation
- voyage optimisation
- maximise ship operability at operational level in a real environment
A COLLABORATIVE PROJECT

- UNIGE – Naval Architecture & Marine Engineering (DITEN)
  - Ship motion modelling
  - Ship propulsion modelling
  - Ship strenght modelling
- UNIGE – Weather Forecast (DICCA)
  - Sea state forecast
  - Surface wind forecast
- ONAIR Srl – (R&D performing SME)
  - Search path algorithms
  - Optimization algorithms
Work Flow

• Hull forms modeling, propulsion system modeling,
• Design Operational area, sea & wind forecast
• Ship motions calculation
• Motions effects on people onboard
• Motions effects on propulsion system performance
• Motions effects on structures (not yet available)
• Ship Operational capability
• Maximise capability: voyage plan optimisation
Workflow
VOYAGE OPTIMIZATION

**INPUT**

- **Ship model**: built upon specific ship design data, (principal dimensions, resistance curves, hull geometry, propeller diagrams, engine consumption curves, etc.)
- **Weather conditions**: forecasted meteo data including wave spectral parameters and wind intensity and direction
- **Minimum/maximum arrival time**
- **User defined constraints**: search area, fixed waypoints, number of manoeuvres, maximum amplitude and acceleration of ship motions, allowed severity (slamming and deck wetness probabilities), maximum loading for engines.

**OPTIMIZATION ENGINE**

The optimization engine search all available routes, according to the given contraints in terms of arrival time, safety, waypoints, etc, comparing the fuel consumption and comfort/safety, computed by suitable indexes. Such quantities can be evaluated by the inclusion inside the optimization engine of a complete ship simulation model.

The search for all available routes is performed according to the orthodromic navigation scheme. The engine adopts the most advanced optimization algorithms, both single and multi-objective, and exploits the specific features of the naval optimization to increase computational performances. The user can explore the full search space and perform sensitivity analysis of optimal routes by varying the imposed contraints.

**OUTPUT**

Optimal routing, including the speed profile to be followed in every route segment.

The route is generated in the standard KML format, allowing an easy representation by Google Earth tools.
Ship Motion

• Ship response
  \[ S_{\eta_i}(\omega, \theta, V) = |H_{\eta_i}(\omega, \theta, V)|^2 S_{\zeta}(\omega, \theta) \]

• Added resistance
  \[ R_{aw}(V) = 2 \int_0^\infty \int_0^{2\pi} \Phi_{aw}(\omega, \theta, V) S_{\zeta}(\omega, \theta) d\omega d\theta \]

• Sea spectrum forecast
  \[ S_{\zeta}(\omega, \theta) \]

• Wind forecast
  \[ V_W \]
\[ R_{\text{ADDED}} = R_{WIND} + R_{WAVE} \]
Engine modelling

- Stationary model
- Engine load limits
- SFOC surface
Route parametrization
Optimal path search: 3D dynamic programming

Start

Arrival

Step 1 2 3 4 5 6

Node \(i\) \((\text{Lat}_i, \text{Lon}_i, t_i)\)

Node \(j\) \((\text{Lat}_j, \text{Lon}_j, t_i + \Delta t)\)

Ship model

Fuel consumption

Speed
Optimal path search: 3D dynamic programming

Nodes propagation

- States at step $k+1$
- Possible arrival times

Pruning strategy

- Minimum f.c.
- Steps
Optimal path search: 3D dynamic programming
Case study

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
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<tbody>
<tr>
<td>Lenght b.p.</td>
<td>182 [m]</td>
</tr>
<tr>
<td>Bream</td>
<td>31 [m]</td>
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<tr>
<td>Draft</td>
<td>9 [m]</td>
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<tr>
<td>Displacement</td>
<td>41577 [t]</td>
</tr>
<tr>
<td>Deadweight</td>
<td>40846 [t]</td>
</tr>
<tr>
<td>Propeller</td>
<td>1 x FPP, 4 blades, 6m Diameter</td>
</tr>
<tr>
<td>Main engine</td>
<td>1x10 MW, 113 RPM 2 stroke diesel engine</td>
</tr>
</tbody>
</table>
High resolution weather forecast
Trade-off curves: fuel vs. time
Genoa - Barcelona
Fuel consumption & EEOI
Engine working points vs beaufort scale
Fuel rate increment vs beaufort scale
Voyage Optimization 1/2
Genova - Barcellona

- Distanza minima percorsa: ca. 350 nm
- Tempo di viaggio considerato: 35 h (velocità media 10 Kn)
- Differenti modalità di viaggio:
  - Rotta a velocità costante
  - Optimizzazione di velocità (S.O)
  - Oottimizzazione di rota e velocità (V.O.)

- Risultati:
  1. Tempo di arrivo vs. consumo totale nei casi considerati
  2. Confronto delle traiettorie nei casi considerati
  3. Confronto dei profili di velocità delle soluzioni V.O a tempi di arrivo differenti
  4. Confronto dei profili di consumo (soluzioni V.O)

Massima riduzione dei consumi riscontrata: 11%
Voyage Optimization 2/2
V.O. vs. S.O. vs. velocità costante

Tempo di viaggio

Profilo di velocità

Profilo di consumo
APPLICATIONS

• MRV monitoring, reporting and verification of carbon dioxide emissions from maritime transport,
• EEOI assessment
• SAR vessel capability optimization
• Naval vessel platform capability assessment
Thanks for your attention

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Simulation Lab

Hardware

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Prof. Giovanni Benvenuto*
Prof. Massimo Figari
Prof. Michele Martelli
Prof. Stefano Savio
Prof. Michele Viviani
Dr. Raphael Zaccone

Prof. Angelo Alessandri (DIME)
Prof. Ugo Campora (DIME)
Prof. Stefano Vignolo (DIME)

2 Ph.D. Students
Research streams

• **Propulsion plant dynamics**
  • Non linear models

• **Control logics simulation**
  • Propulsion controller
  • DP controller
  • Speed pilot
  • Autonomous navigation

• **Energy efficiency optimisation**
  • Weather routing
  • Power management

• **Condition based maintenance**

• **Alternative propulsion plants**
  • LNG
  • Hybrid Sail-Diesel-Electric Propulsion
SIMULATION MILESTONES

• 1994: diesel engine tabular model, propeller tabular model, fishing boat model
• 1996: shaft line model with torsion, thermodynamic diesel model, model of “San Giusto”
• 1998: water jet model, diesel engine model with EGR
• 2000: model “Nave EXCELSIOR” and measurement campaign
SIMULATION MILESTONES

• 2002: diesel engine model with sequential turbocharger, model of “Comandante Bettica” and measurement campaign

• 2003: manoeuvrability of planing hulls
SIMULATION MILESTONES

2004 - 2007: propulsion control system developed by simulation (RT-HIL) for “Cavour”, and measurement campaign

2010: low speed manoeuvrability model, model “La Superba” and measurement campaign
SIMULATION MILESTONES

2009 - 2012: propulsion control system for CODLAG and 6 DOF manoeuvrability model of “FREMM” with measurement campaign

2013: 4 DOF manoeuvrability model for planning hull
SIMULATION MILESTONES

2013: Amerigo Vespucci: development of control system for combined sail and diesel propulsion

2013-2015: Coast guard patrol vessel: Diciotti: 3 DOF low speed model for dynamic positioning application
MODEL BASED DESIGN PROCEDURE

DESIGN

MODELLING

OPTIMIZE

TEST

REAL SYSTEM