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Ship voyage optimization for safe and energy-efficient navigation: A dynamic programming approach

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ABSTRACT

The paper presents a 3D dynamic programming based ship voyage optimization method, aiming to select the optimal path and speed profile for a ship voyage on the basis of weather forecast maps. The optimization is performed in accordance to a minimum fuel consumption strategy taking also into account ship motions and comfort. The optimization is carried out in a discretized space-time domain: the ship voyage is parametrized as a multi-stage decision process in order to formulate a dynamic programming optimization problem. Waves and wind conditions are estimated for each route segment by weather forecasting maps then seakeeping related indexes and fuel oil consumption are computed taking into account wave-induced ship motions and added resistance. The best routing solution is thus selected by a dynamic programming algorithm developed and implemented by the authors. Results and discussion of the proposed method are presented for a merchant ship application in a test case voyage through the Northern Atlantic Ocean and compared to the constant speed great circle solution.

1. Introduction

In the recent years the continuously increasing availability of reliable weather forecast data has significantly improved the safety of the ship voyages, helping the operators to select proper routes to avoid rough weather and have an estimate of the time of arrival (ETA) and the voyage cost. Moreover, increased attention is put nowadays to seakeeping abilities of ships in order to improve passage safety even with rough sea. However, most of the time medium intensity weather conditions are encountered; these conditions do not affect ship safety but influence fuel consumption and comfort on board. In this framework optimization algorithms can provide a significant support to the decision making process in order to select the best choice in sight of one or more objectives.

The selection of the optimal route combines a number of objective functions as well as various constraints. In principle a ship voyage is characterized by a starting point, an arrival point, a constrained arrival time window, eventually a number of fixed way points. Geographical (static) constraints need to be considered as well: for example, the shore line, traffic separation schemes, restricted areas, bathymetry. Realistic modeling of the ship behaviour in relation to weather conditions is crucial to correctly estimate and compare the ship performance in different conditions. Decision making needs to be based on ship response, rather than on external conditions (Chen, 2013), in order to better fit different ship types, shapes and dimensions: different ships have different responses in the same weather and speed conditions. Ship and human life safety, fuel consumption, energy efficiency, crew and passengers comfort, voyage time management, control of delays are possible tasks which can be pursued by voyage optimization.

Weather routing services and codes available on the market are usually not supported by public domain scientific papers due to confidentiality reasons. In author's knowledge very often they are based on the principle of ‘storm avoidance’. The typical approach is to implement a set of generic speed reduction curves in function of sea state parameters (for example the Beaufort Wind Force Scale) and a number of global ship parameters (for example, displacement and length). The fuel consumption is estimated on the basis of empirical relationships, while ship hull geometry, seakeeping abilities and propulsion system features are neglected. This approach can lead to unnecessary diversions to avoid rough weather, badly affecting the fuel consumption. The ship speed decrease in rough weather can occur as a consequence of two reasons: involuntary speed reduction due to the additional resistance induced by wind and waves, and/or voluntary speed reduction to avoid navigation hazards and excessive ship motions which would result in propeller racing, slamming or green water. Additional constraints related to safety

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and/or comfort might thus be considered to limit ship motions or wave induced forces. A proper ship response modeling is crucial in order to correctly estimate these phenomena on a case by case basis. Furthermore a model of the actual propulsion system is essential in order to predict the propulsion performances in rough sea and to take into account the propulsion system limits when steaming into stormy conditions. Moreover, ship speed changes need to be managed by the optimization algorithm in order to use the speed adjustment as a rough weather avoidance parameter in addition to course deviation but within the propulsion system thrust/power capability.

The weather routing problem has been addressed by many authors in the past and different approaches have been proposed. The first pioneer works were centred on finding the minimum time of arrival on a voyage (James, 1957; Zoppoli, 1972; Papadakis and Perakis, 1990) however most of the authors neglected the ship response behaviour in rough sea. More recently, voyage optimization has been approached in a wider sense, taking into account ship motions and/or fuel consumption. The most used techniques include multi objective genetic algorithms (Marie et al., 2009; Maki et al., 2011; Vettor and Guedes Soares, 2016; Zaccone et al., 2016), deterministic enumerative algorithms (Lin et al., 2013; Fang and Lin, 2015; Shao et al., 2012), brute force optimization (Lu et al., 2015), local search algorithms (Safaei et al., 2015). Simulation of ship behaviour in rough sea have been proposed in the past by several authors: Journée (1976); Journée and Meijers (1980) proposed some guidelines to develop a ship model to take into account either propulsion and ship motions. More recently weather routing oriented propulsion simulation, without optimization, have been published by Coraddu et al. (2013). Crew and passengers comfort evaluation techniques for human bodies exposed to mechanical vibrations and accelerations are suggested in the ISO 2631-1: 1997, based on the methods proposed by O'Hanlon and McCauley (1973), and Lawther and Griffin (1988). The authors gained extensive experience in steady state and transient modeling of ship propulsion systems (Altosole et al., 2008, 2014, 2016, 2017; Martelli et al., 2014a,b) mainly for control design purposes.

In the here presented work ship voyage optimization problem is tackled by means of a problem-specific algorithm based on 3D dynamic programming (3DDP) coupled with a dynamic ship propulsion model and with weather forecast data. Fuel oil consumption is considered as the objective function to minimize while ship motions and expected time of arrival (ETA) are used as constraints. In particular, ship motions based constraints are imposed on probability of slamming and deck wetness (Journée and Meijers, 1980), motions sickness index (MSI) (O'Hanlon and McCauley, 1973), and lateral forces (Perez, 2006). The constraints allow to implicitly take into account any voluntary speed reduction in presence of rough weather, while involuntary speed reductions are simulated by considering the effect of the ship resistance increase due to waves (Journée, 1976) on the propulsion system. Wave and wind forecast data are considered in function of time and geographical coordinates: wave significant height, mean period, direction and wind speed components are obtained via space-time interpolation in the forecast maps. The obtained data are used to estimate ship motions and added resistance in order to assess the required engine power and fuel consumption via steady state ship propulsion simulation. The fuel consumption is used as the cost function to evaluate each route segment and compute the optimal solution. DP approach fits well to 'best path search' problems (Bellman, 1958), so is one of the classic choices to tackle ship voyage optimization tasks. In particular, the problem is solved by exhaustively exploring a discretization of the search domain while very little restrictions are put on either the objective function and optimization constraints because no derivatives are calculated. The deterministic nature of the algorithm may be seen as an advantage with respect to heuristic global search algorithms. Nevertheless, in a weather routing framework, the benefit is partially limited by the fact that input data is affected by significant uncertainties. DP method has some drawbacks in terms of compuatation speed. However, the presented implementation includes proper problem-specific pruning strategies to boost computational efficiency. The implemented algorithm performs an efficient systematic exploration of the domain of the solutions, defined by a three dimensional space time grid. The result of the optimization is a sequence of waypoints and intermediate times determining the ship trajectory and speed profile. With respect to present state of the art weather routing and voyage optimization methods, the presented approach presents a twofold benefit: it is based on a detailed description of the propulsion system allowing a realistic evaluation of the fuel consumption and exhaust emissions versus ship speed and it implements an innovative 3D dynamic programming optimization routine which allows to manage both ship route and speed profile.

To this end, the main tasks to be solved, in order to manage the route optimization problem, are:

- weather forecast data availability and management;
- ship propulsion performance and hydrodynamic response modeling;
- optimization problem formulation and solution.

A short overview is given to the first point, which is considered as input data. The paper is centred on the second and third points which are going to be described in detail. Finally, a case study is analysed and results are shown in order to highlight the features of the presented approach in a realistic case.

2. Weather conditions

Two weather actions are considered: waves and wind. Wind forecast data is provided in terms of wind speed components (u, v) as a function of geographical coordinates (λ, φ) and time t. Forecasted wave significant parameters are provided as well in function of the same variables, in particular significant wave height $H_{\frac{1}{3}}$, wave period T_1, and direction θ. The wave parameters are used to fit a parametric spectral formulation. ITTC 84 JONSWAP spectral formulation with a cosine square spreading function is used:

$$S(\omega, \theta) = 155\frac{H_{\frac{1}{3}}^2}{\omega^5 T_1^4}\exp\left(-\frac{944}{\omega^4 T_1^4}\right)\gamma^Y\frac{2}{\pi}\cos^2\theta \tag{1}$$

being:

$$Y = \exp\left[-\left(\frac{0.191\omega T_1 - 1}{\sqrt{2}\sigma}\right)\right] \tag{2}$$

where ω is the wave circular frequency, and $\gamma = 3.3$ for Northern Atlantic applications. The choice of the spectral formulation can significantly affect the results, as it directly influences the ship motions and resistance. In particular, a correct selection of parameter γ should be made in function of the geographical area in which the optimization is performed. Moreover, real and parametric spectra may differ significantly in presence of crossing seas (Mentaschi et al., 2015; Spentza et al., 2017): these aspects will be deeply investigated in the future research, while the presented work is mainly focused on investigating the potential of the optimization procedures in a voyage optimization framework.

3. Ship model

The ship numerical model allows to estimate the fuel consumption in given geographical positions, weather conditions and ship speeds. The model is structured in four main blocks:

- hydrodynamic resistance calculation
- ship motions and comfort assessment
- propeller performance prediction
- engine performance prediction

The model arrangement is shown in Fig. 1. At any time and