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A real-time strategy-decision program for sailing yacht races

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ABSTRACT

Optimal decisions for a skipper competing in a match race depend on a number of factors, including wind speed and direction variations, behaviour of the opponent, sea state, currents, racing rules. Expert sailors are able to combine observations on these various factors and process them to take optimal decisions. This study presents an attempt at emulating this decision process through a computer code that can be used in real time to advise on race strategy. The novelty of the proposed method consists in combining various approaches for the multiple factors affecting the decision process.

The wind variability is modelled with the use of neural networks, to produce a short-term wind forecast. The willingness of the sailor to risk is modelled using coherent-risk measures. Experimental results are used to quantify the loss of speed due to the presence of a nearby opponent. Finally, all these factors are combined through dynamic programming to compute an optimal course, based also on information on the current and yachts performance. The program is tested modelling the last 13 races of the 34th America's Cup, and results show that the route computed is close to the shortest possible route computed assuming perfect knowledge of sea conditions.

1. Introduction

A yacht race is a competition where two or more boats race each other to complete a certain course in the shortest time. Traditionally, the problem that a sailor has to solve is addressed as an optimisation problem consisting in going from point A to point B in the shortest possible time, under certain constraints given by the dynamics of the yacht and racing rules. This approach however doesn't really capture the competitive aspect of a race. In fact, the real aim of a sailor is not to get to the finish line as fast as possible, but rather to get there before their opponent(s). Moreover, the speed of a sailing yacht is highly dependent on the behaviour of the wind. A sailor doesn't have perfect knowledge of the future wind patterns, and therefore the problem must be addressed as a stochastic problem, based upon probability distributions of the wind behaviour. This paper presents the development of a routing algorithm aimed an enhancing the probability of winning during a race between two yachts, by considering multiple issues of stochastic wind changes, presence of the opponent, and risk management.

1.1. Background on yacht racing

The speed of a sailing yacht depends on the wind speed and the course wind angle (TWA, the supplementary angle between the wind velocity and the boat heading). Fig. 1 presents an example of boat speed (BS) as a function of the TWA for a given wind speed in a polar diagram. A polar plot of this kind, which may include different curves associated to different wind speeds, is the conventional way of presenting the boat speed, and although the actual BS can depend on other factors (such as waves and crew), it is considered as a characteristic of a yacht.

As shown in the plot, the highest values for the BS are achieved when sailing at a TWA of approximately 90° (on a *beam reach*). Conversely, when the TWA tends to zero, BS tends to zero. Therefore, when sailing upwind (for instance, from a downwind mark to an upwind mark), the most effective route consists in a zig-zag in the wind direction, sailing at a TWA of 35–50° (*close hauled*). In this case, a skipper's aim is to maximise the speed in the upwind direction, which means to find the TWA such that the projection of the boat velocity on the upwind direction is a maximum. The corresponding velocity is referred to as Velocity Made Good (VMG) and is shown in red in Fig. 1.

The VMG can be defined also for downwind sailing. In fact, as shown in Fig. 1, even if the velocity is not null when the TWA is 180°, the maximum projection on the downwind direction for this example is obtained at angles of approximately 150°. However, the optimal angle for downwind sailing can have significant variations depending on the yacht geometry.

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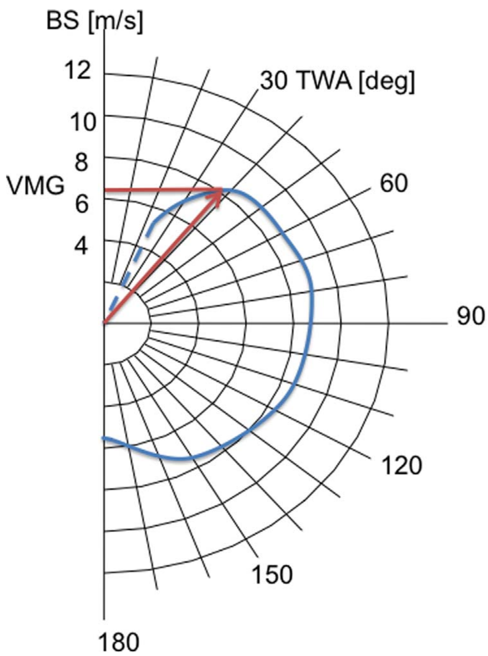

Fig. 1. Example of polar diagram.

Yacht races are held in many different formats and levels: in the case of a *match race* only two boats face each other, while in a *fleet race* the number of participants can be very high. Fig. 2 shows an example that appears in most races, where a yacht has to sail between two marks aligned with the wind direction. In the example shown, the yacht is sailing upwind, and as previously noted the VMG gives the best angle to sail at. This means that there will be a need for a certain number of changes of direction, called *tacks*, two of which are underlined by red arrows. The tacks lead to a time loss, as when changing direction the yacht is not sailing at maximum VMG. However, they may also lead to an advantage when a tack is performed to react to a change in wind direction. A fundamental question for a sailor is when it is the right choice to tack.

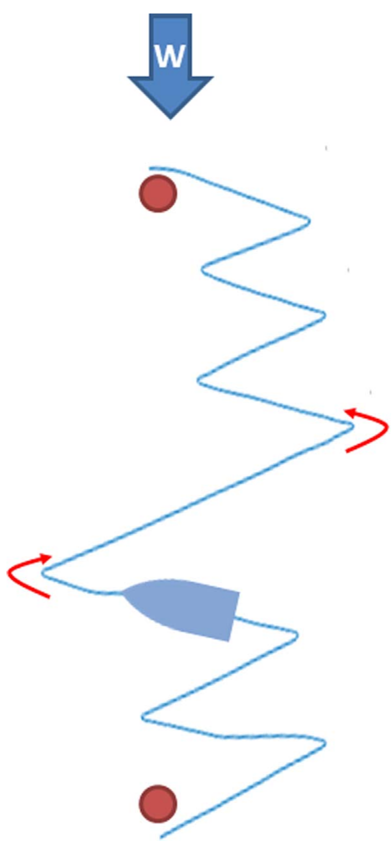

Fig. 2. Example of upwind leg.

1.2. *State of the art on yacht racing strategy and contribution of present work*

Most of the academic research in the field of competitive sailing is dedicated to analysing the fluid dynamics of sailing yacht, with the aim of maximising their performances. However, in recent years more attention has been given to the topic of racing tactics, and to the development of Race Modelling Programs (RMP).

Philpott and Mason (2001) and Philpott (2005) addressed the problem of finding the optimal route by introducing the use of dynamic programming. The race area is discretised and the wind is modelled as a discrete-time Markov Chain. At each step, the only available information about the wind is the current state and a probability distribution for the next state. The outcome of the algorithm is a policy aimed at minimising the expected time to complete the race leg. DP is shown to be an effective way to address the problem and is used in many subsequent studies, including Dalang et al. (2014), Tagliaferri et al. (2014) and the present work. DP has also been extensively investigated for decision-making in different applications, including energy (Clement-Nyns et al., 2010), logistics (Hall and Potts, 2003), medicine (Sahinidis, 2004). Markov Chains have been used also by Ferguson and Elinas (2011), in a study focussed on finding optimal routes for inshore racing, in presence of landmasses influencing the wind. In this case, the environment is considered fully observable (i.e. the wind behaviour is known), while the yacht's dynamics is uncertain.

Philpott et al. (2004) also addressed the issue of interactions between yachts. In this work an RMP is implemented to assess virtual competitions between yachts of different designs, to quantify the advantage of different candidates in a race scenario. The physical interactions are modelled by developing a theoretical model of a wind shadow region, using a penalty which penalises the downwind yacht and rewards the upwind yacht. Other studies have developed a fleet race simulator and used a lifting line method to compute the covering and blanketing effects in a fleet race (Spenkuch et al., 2008, 2010, 2011). Subsequently, Aubin (2013) and Richards et al. (2012) have provided experimental data showing the changes in the wind speed and direction observed by a yacht when sailing close-hauled to another yacht. This experimental data can now be used to compute the speed changes of a boat due to the relative position of her competitor.

The risk attitude of the sailors was recognised to be a crucial factor in the work by Scarponi et al. (2008), who introduced risk modelling in terms of payoff matrices allowing the sailor to choose the option of delaying a tack. Tagliaferri et al. (2014) included the risk model in the decision algorithm, and showed that rather than finding a strategy that minimises the expected time to complete a race leg, a strategy aimed at maximising the probability of completing before the opponent can improve the probabilities of winning. This can be achieved by having a risk-seeking behaviour when losing, and a risk-averse behaviour when leading the race. In this case, the attitude of the sailor depends on their relative position with respect to the opponent.

One of the most recent and complete work on yacht routing is represented by the computer program described in Dalang et al. (2014), produced in collaboration with the Alinghi team for the 2007 America's Cup. In this study, a program for the computation in real-time of the best route is presented. The program is extensively tested both through simulations and on the water, and represents the most advanced published work on real-time routing for yacht races. The wind is modelled as a Markov Chain based on past measurements, however no information on wind forecast is used. In the present work, we combine some of the aforementioned techniques to produce a