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Wind direction forecasting with artificial neural networks and support vector machines

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ABSTRACT

We propose two methods for short term forecasting of wind direction with the aim to provide input for tactic decisions during yacht races. The wind direction measured in the past minutes is used as input and the wind direction for the next two minutes constitutes the output. The two methods are based on artificial neural networks (ANN) and support vector machines (SVM), respectively. For both methods we optimise the length of the moving average that we use to pre-process the input data, the length of the input vector and, for the ANN only, the number of neurons of each layer. The forecast is evaluated by looking at the mean absolute error and at a mean effectiveness index, which assesses the percentage of times that the forecast is accurate enough to predict the correct tactical choice in a sailing yacht race. The ANN forecast based on the ensemble average of ten networks shows a larger mean absolute error and a similar mean effectiveness index than the SVM forecast. However, we showed that the ANN forecast accuracy increases significantly with the size of the ensemble. Therefore increasing the computational power, it can lead to a better forecast.

1. Introduction

The speed of a sailing yacht depends on the wind speed and the course wind angle (the supplementary of the angle between the wind direction and the boat velocity). The boat speed can be represented as a polar diagram, such as the one shown in Fig. 1, where the radial coordinate is the boat speed of an AC72-class boat, for a fixed wind speed, while the angular coordinate is the boat's heading with respect to the true wind direction (data from America's Cup Event Authority, 2013). The dependency of the boat speed on the wind velocity is a key element when deciding the tactics during a yacht race. For instance, when navigating around the world, experienced sailors take advantage of large-scale weather changes, and for inshore races lasting less than one hour, minimal wind shifts can be used to gain an advantage on the competitors. In the latter case, the ability to forecast very-short-term wind changes can make the difference between a win and a loss. A prepared sailor consults wind forecasts before starting the race, and this is usually used to build a strategy aiming at sailing in the racing area where a higher wind speed and a more favourable wind direction are expected. During the race, it is possible to use only the information which is collected on board, including wind speed and direction, which are measured with a cup and vane anemometer on the top of the mast. In the present paper, we present two methods to forecast very-short-term wind shifts based only on the wind direction measured on board during the race. The proposed wind forecast is aimed at complementing the longer-term weather forecast available to the sailors up to the beginning of the race.

1.1. Racing tactics

A typical America's Cup race is made of several turns around an upwind and a downwind mark, where the marks are aligned with the wind. For instance, in an upwind leg, the boats start from the downwind mark and have to reach the upwind mark, located upstream. As shown in the polar plot in Fig. 1, it is not possible to sail directly upwind. The fastest route consists in keeping an optimum course wind angle that maximises the boat velocity in the upwind direction, i.e. the velocity for which the projection on the vertical axis of the plot in Fig. 1 is a maximum. This velocity component in the wind direction is known as VMG. As an example, the optimum course wind angle in an upwind leg for a wind speed of 26 knots is shown in Fig. 1, together with its projection. In most wind conditions this optimum angle is roughly 45°. Because the boat is not sailing straight towards the upwind mark, at a certain

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point a change of direction of about 90° will be needed. These changes of course are called tacks. While tacking, the course wind angle decreases from the optimum value, leading to a speed loss. Therefore the total number of tacks should be minimised. Typically, an AC72-class yacht takes about 20 s to complete a tack, and during the manoeuvre the average boat speed is approximately 70% of the optimum speed. Therefore, a tack leads to a loss of about 6 s.

If the wind direction is constant, then the optimum route includes only one tack. Conversely, when the wind direction varies such as in real conditions, then the sailor can tack between two consecutive wind shifts in order to gain an advantage. However, this advantage must be greater than what is lost due to undertaking the tack. There is a high number of possible scenarios that can arise during a race and the problem of taking the best decision is not trivial (Philpott and Mason, 2001). There are however some situations in which the best decision can be easily taken when a sailor is able to foresee how the wind is going to behave. In the following the two most likely scenarios are presented.

Fig. 2 shows the route followed by two boats in order to reach an upwind mark in two different wind conditions. In the first case (left) the wind alternately shifts by 3° to the right and to the left. The first shift is towards the right and, while the two boats sail at their optimum course wind angles, they chose to sail in different directions. Both boats tack at every wind shift. The black boat is always sailing towards the left-hand side of the race course when the wind shift is towards the right, and vice versa when the wind shift is towards the left. Conversely, the grey boat has the opposite strategy. Therefore, the black boat is always sailing to a closer angle to the mark than the grey boat, she sails a shorter course and she arrives first to the mark. The winning tactic of the black boat is that she always maximises her velocity towards the mark. However, this is not always a winning tactic. In fact, in the second case (right), the wind constantly shifts towards the right. The two boats follow the same strategy as in the previous case: experiencing a wind shift to the right, the black boat sails towards the left and the grey boat sails towards the right. Being the wind constantly shifting to the right, the two boats never tack until they reach a lay line, i.e. where a tack allows the mark to be reached without any further tacks. The black boat needs to sail most of the race course before reaching the lay line and being able to tack to the mark, while the grey boat reaches the lay line before the black boat. In this case, even if the two boats have pursued the same strategy based on the wind observed at the time, the resulting course sailed by the black boat is longer than the course sailed by the grey boat, because the wind shifted regularly in the same direction instead of alternating to opposite directions. This shows that the tactical decision cannot be based on the wind direction observed at the time, but that the future wind shifts must be foreseen in order to develop a winning strategy.

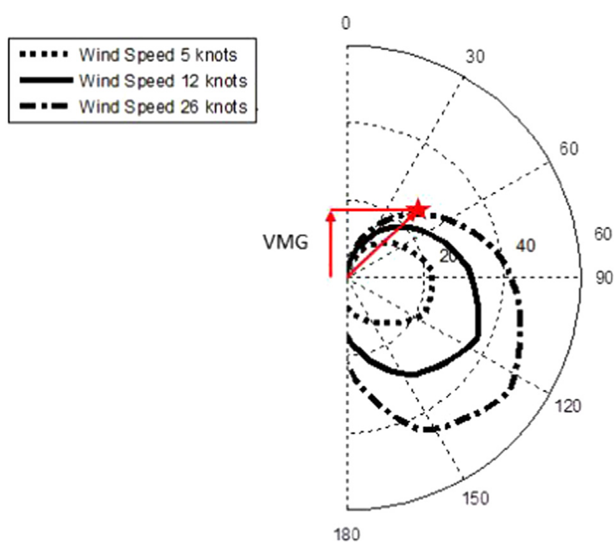

Fig. 1. Polar diagram of an AC72-class yacht.

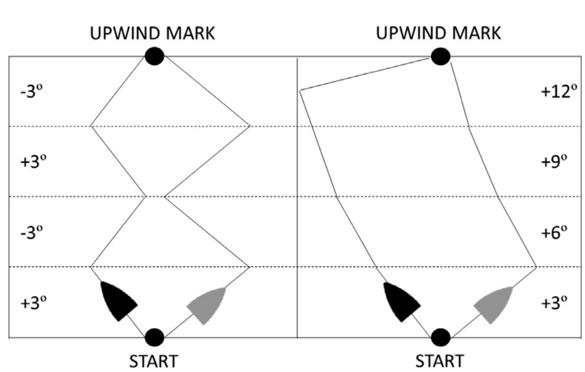

Fig. 2. Yacht routes in oscillating wind (left) and in a permanent wind shift (right).

Fig. 2 shows that the optimum strategy depends on if the wind shift has a wavelength shorter or longer than the distance to the lay line. If the race course is confined by boundaries, such as shore lines or forbidden areas, then wind shifts with wavelength up to the distance to the boundary should be considered.

In the 34th America's Cup, the racecourse was bounded by imaginary lines in order to allow the spectators to be closer to the racing boats. The boats took about two minutes to sail from one boundary to the opposite one, thus the maximum wind shift period of interest was about two minutes.

Consider the black boat in Fig. 2. The boat starts from the centre of the course, she sails for say one minute, then tacks and comes back to the centre of the course. Say she took two minutes plus 6 s for the tack. If the optimum course wind angle is 45°, in two minutes a shift of 3° would lead to an advantage of about 6 s on the grey boat. On the contrary, if the grey boat had tacked at the start and followed the black boat from the beginning, she would be 6 s behind the black boat due to the time spent to tack at the start. Therefore a wind shift of 3° is the threshold at which the decision of tacking or sailing in the same direction has to be made.

1.2. Artificial neural networks

We use artificial neural networks (ANN) to accurately forecast wind shifts larger than 3° for the two minutes ahead. ANNs are computational models that emulate the ability of the human brain to learn from experience, similarly, for instance, to the capability of a human sailor to make predictions based on his lifelong experience. In the literature it is possible to find a vast number of applications where ANNs have been successfully used, especially to solve problems which are peculiar of humans, such as speech recognition (Morgan and Bourlard, 1995), image classification (Park et al., 2004), and control of moving robots (Fierro and Lewis, 1998).

The constitutive unit of a neural network is a neuron, which is a singular processing unit that takes several inputs originating from other neurons, and produces an output that is then transmitted to other neurons. A representation of the structure of a neuron is shown in Fig. 3. A neuron can be broken down into the following components:

1. A set of connecting links, called synapses, where the ith synapse is characterised by a weight w_i (synaptic weight).
2. An adder within the neuron that sums each ith input multiplied by weight w_i.