ROBO-YACHT: A HUMAN BEHAVIOUR-BASED TOOL TO PREDICT THE PERFORMANCES OF YACHT-CREW SYSTEMS

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Introduction

The 'toolbox' of a 21st Century yacht designer includes experimental techniques and numerical models to investigate the complex physics of a sailing yacht. Experimental and numerical data are the building blocks of Velocity Prediction Programmes (VPPs) (see Kerwin & Newman, 1979). These can be used either to rank design alternatives (e.g. different hull shapes), to assess the potential of an existing yacht (e.g. maximum speed given the sea state) or for handicapping purposes. While these tools can be further refined and the reliability of predictions improved, the main area for performance gains is related to the 'quality' of the crew. In fact, competitive sailing is an uncertainty-rich discipline and the expertise of the sailor is still the key to winning races. Therefore, in order to derive reliable predictions, yacht models and crew models should be coupled and the joint performances should be assessed.

The present study aims at predicting the performance of yacht-crew systems, by including numerical models for human behaviour within those referred to the yacht dynamics. In particular, the problem of decision-making under weather uncertainty is formulated in terms of a game of chance having nature as a second player and involving risk. Within this context, it is shown that decision-making models often used in management sciences can advantageously be used. This approach has led to the development of a sailing simulator referred to as 'Robo-Yacht', based on the International America's Cup Class.

In order to demonstrate the effectiveness of this approach, a case study is investigated that involves three strategical alternatives and four possible weather scenarios: gains and losses are assessed through the simulator and a formula to express expected payoffs is derived. Moreover, decision-making strategies based on the maximization of expected payoff or expected utility are investigated with the aid of the sailing simulator. The 'automatic crew' can actually make decisions that appear to be consistent with widely accepted principles of race strategy.

Methods

Main Features of the Sailing Simulator

The in-house sailing simulator used for the present study was designed in order to simulate the dynamics of sailing yachts, to model fleet races, to provide in-line and off-line animations and to give a user the possibility of controlling a yacht in real-time. In order to do so, the simulator is composed of:

- a physics engine: it solves the equations governing the motion of the sailing yacht (Masayuma et al., 1995), in order to update the yacht position, velocities and accelerations at each time step throughout the simulation;
- crew models: automatic crews have been implemented in order to model the steering, the sail trimming and the navigation around the race course;
- weather models: variations in the wind speed and direction (of a deterministic or a stochastic nature);
- a post-race analysis module: to evaluate yacht-crew performances all over the race.

Additional features are made available for real-time race animations:

- a virtual 3d world: yachts, race scenario (e.g. sea, marks, landscape), onboard cameras;
- onboard instruments: to monitor the yacht state in real-time (e.g. speed, sail forces, wind angle).

The automatic navigation is based upon rules of thumb of a strategical and a tactical nature. The former set of rules deal with weather uncertainty, while the latter are referred to the opponents. These rules were derived with the help of questionnaires submitted to skilled athletes. Also, the athletes' feedback has been crucial for the identification of the key situations in a race, where appropriate decisions are likely to make the difference. In the following Section a 'decision matrix' is derived for a given test case and a rule-based navigation is considered. Furthermore, a decision-making function is under development in order to model the cue pick-up process and the effects of time pressure. Due to the ongoing nature of the study, this topic will be addressed at the Congress.

The geometry of an IACC hull referred to as 'M566' has been implemented in the present version of the simulator; several experimental tests have been carried out on the M566 model at the University of Southampton (Berk, 2005), and a fairly large amount of data is available on its hydrodynamics and manoeuvering characteristics (see Scarponi et al., 2007, for further details on the simulator).

Definition of a Decision Matrix and Test Case

A test case is investigated where a boat of the IACC-M566 class is racing solo against the clock. The environmental conditions are characterized by flat water and changing wind direction. Wind speed is constantly 4 m/s. The course is a two miles upwind leg with two marks: No.1 and No.2. The race starts at Mark No.1 at time $t_0 = 0$ and boats are required to 'beat' up to Mark No.2 (the 'upwind' Mark) while minimizing the racing time by taking advantage of wind changes. The maximum time allowed for the race is $t_{end} = 800$s. Due to the physics of sailing, a yacht cannot sail to an upwind mark in a straight line: its course must be at an angle with the wind direction and must necessarily include manoeuvers

or ‘tacks’. The present test case investigates the timing of tacks, while the boat handling and the tacking technique are constant throughout the race in order to reduce the number of simulation variables.
Between t_0 = 0 and t_1 = 120s, the boat reaches a state of aero-hydrodynamic equilibrium while sailing in a steady Northerly breeze. During this stage, the yacht sails ‘on port’ i.e. with the wind hitting the left-hand side of the hull first. After t_1, the automatic crew takes over and is given the possibility of tacking onto starboard (i.e. with the wind hitting the right-hand side of the hull first).
At time t_2= 200s, the True Wind direction shifts towards East by 10° (+10° header). A decision-making problem therefore arises, which can be investigated by using a decision matrix. This is composed of alternatives $A_1,\dots,A_m$ and scenarios $S_1,\dots,S_n$. The matrix is arranged in a way that, when A_i is the selected alternative and scenario S_j occurs, the decision maker is ‘rewarded’ with a payoff $C_{i,j}$. In addition, a probability distribution $\{ P_1 , P_2 ,..., P_n \}$ can be associated with $\{ S_1 , S_2 ,..., S_n \}$, such that P_j represents the probability that outcome S_j occurs. If a ‘normative’ decision-making strategy is considered, the most advantageous alternative is the one yielding the largest expected payoff E_i (as in Eqn.1).

$$E_i = \sum_{j=1}^{n} P_j C_{i,j} \tag{1}$$

Three alternatives (rows A_1 to A_3 of Tab.1) are considered for the present case: tacking immediately onto starboard, not tacking unless further windshifts occur and delaying the tack by 60 seconds. Four possible weather scenarios or ‘outcomes’ are set (columns S_1 to S_4 of Tab.1), namely:
S_1: True Wind Speed and True Wind Angle constant from t_2 = 200s onwards;
S_2: True Wind shifts further right (additional +10°, i.e. a header for port tackers) at t_3 = 320s;
S_3: True Wind shifts back North (-10°) at t_3 =320s;
S_4: True Wind shifts back North (-10°), at t_3 =320s, then further left by -10° at t_4 =440s.
The payoffs are calculated with the aid of the simulator, by means of Eqn.2 below

$$C_{i,j} = \left(1 - \frac{DMG^{*} - DMG_{i,j}}{DMG^{*}} \right) * 100 \tag{2}$$

where $DMG_{i,j}$ is the distance sailed towards the mark (equal to zero if the yacht sailed at right angles to the mark itself) when considering the i-th strategical alternative and the j-th weather scenario. DMG* is the reference distance sailed in 10 minutes at the surge speed $u_1 = u(t_1)$. This yields payoffs within the range [0;1], where higher payoffs correspond to a higher ‘benefit’ for the decision maker.
Once the initial decision is made (A_1, A_2, or A_3), the yacht is always sailed according to a unique set of strategical rules: for example, the navigator would always call for a tack on 10° headers or more. This propagates to the whole navigation the positive/negative effect of the single decision made at t_2.

Results
Let us assume that all weather scenarios are equally likely to occur (P_j= 0.25 for j = 1 to 4). As shown in Table 1, higher payoffs are expected when selecting alternative A_1. Alternative A_3 is the ‘second-best’ choice, despite the gap between $C_{2,j}$ and $C_{3,j}$ varies. When the judgement is made across scenarios rather than across alternatives, i.e. choosing an alternative first and then considering all possible scenarios, it can be observed that higher payoffs are always obtained under scenario S_2.
For example, let us consider scenario S_2 (persistent windshift to East): if alternative A_1 was selected (dotted line track of Fig.2), the yacht would tack just once i.e. onto starboard, at t_2. Any further windshift to the right would indeed represent a lift for starboard tackers, yielding therefore higher DMGs. Conversely, if alternative A_2 was chosen (solid line track of Fig.2), the yacht would still be sailing on port at t_3, when hit by the subsequent 10° windshift: this would represent a further header for the port-tacker and the navigator would therefore call for a tack onto starboard. In conclusion, the lower payoff ($C_{2,2} < C_{1,2}$) is due to a 120 seconds beat on the disadvantageous tack. These considerations are consistent with widely known principles of race strategy.
The above results are referred to a linear relationship between payoff and utility, in the sense that an alternative yielding twice the payoff is also twice as desirable. However, when the individual attitude towards risk is taken into account, such a relationship may be of a non-linear nature (e.g. quadratic functions for risk-takers) and choices are based upon a maximization of expected utility (Kelly, 2003). Based on this approach, a sensitivity analysis was carried out and a risk function was derived in order to estimate how the judgement of the automatic crew is biased by risk attitude. A risk function is also derived in order to take into account opponents’ choices and, where necessary, modify the strategic plan accordingly. Although this topic cannot be covered here due to space constraints, methods and results will be presented at the Congress.

Table 1. Decision matrix at t_2 = 200s.

Alternative	S1	S2	S3	S4	Exp. Payoff
A1 (tack)	62.47	72.94	51.77	58.77	61.49
A2 (don't tack)	34.69	66.67	47.29	55.80	51.11
A3 (60s delay)	59.88	69.71	48.43	55.45	58.36

Figure 1. Interactive sailing simulations.

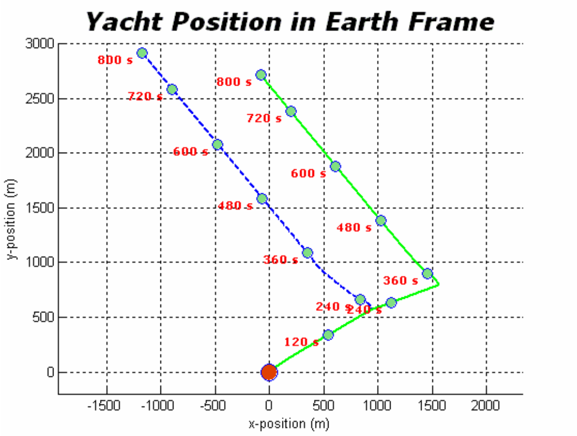

Figure 2. Scenario S_2 : dotted line track for choice A_1, solid line track for choice A_2

Discussion / Conclusions

Within the Sport Psychology domain, papers such as Araùjo et al. (2005) report the use of computer simulated regattas to clarify the behaviour of expert sailors. Furthermore, non-interactive racing simulators such as that described in Philpott et al. (2004) are used in the Naval Architecture domain, either to evaluate prototypical racing yacht designs and to improve existing ones. The present work aims at partially bridging the gap between the two fields, by incorporating human behavioural models and a 'decision-making engine' into an in-house sailing simulator based on the physics of an America's Cup Class yacht. The 'decision-making engine' is modelled in terms of rules-of-thumb derived by questionnaires submitted to skilled sailors. The tool can be used to assess the performances of existing yachts, predict the impact of design variations and estimate human-in-the-loop effects. The tool can perform entirely automatic simulations or run in interactive mode. In the latter case, a user is given the control of a yacht (i.e. rudder adjustments, sail trimming) and real-time routing decisions can be made. Simultaneously, the race is displayed in real-time within a 3d virtual scenario, while a feedback on boat performances is provided by onboard-like displays. This feature can be used to investigate the information pick-up and processing, as well as behavioural patterns of beginners and experts. Building on this, the modelling of automatic crews can be further refined and tailored to different levels of expertise.
The present study shows the application of the simulator to a decision-making problem frequently encountered in sailing: a possible course change (a 'tack') due to a change in the wind direction. Tacking on the windshift can give the crew an advantage, provided that the shift is sufficiently large and stable to compensate the speed lost due to the maneuver. This case is investigated by means of a decision matrix where three possible decisions and four possible weather scenarios are considered. The decision strategy is based on the maximization of expected payoff (decision-making under uncertainty) or expected utility (decision-making under risk); in the latter case, the crew's attitude towards risk is modelled. Results are consistent with widely accepted principles of racing strategy.

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