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INTERACTIONS BETWEEN YACHT-CREW SYSTEMS AND RACING SCENARIOS COMBINING BEHAVIOURAL MODELS WITH VPPS

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SUMMARY

Considerable progress has been made in the development of Velocity Prediction Programs (VPPs) suitable for analysis of racing yacht performance. In addition, investigations on yacht dynamics (i.e. optimal tacking procedure) are now available. While these tools will no doubt be further refined and computations speeded up, there is also a need to assess the performance of the yacht's helmsman and crew. The scope of the present study is the prediction of the performances of a yacht-crew system as a whole, by deriving numerical models for human behaviour alongside with those referred to the physics of yacht motion. The latter issue, the mechanical side of the problem, is analysed by solving yacht equations of motions in the time domain; crew inputs in terms of yacht steering and sail trim are considered. The yacht-crew system can sail a racecourse in an arbitrary wind pattern, according to strategic rules and given decision making schemata.

NOMENCLATURE

[Symbol]	[Definition]
VPP	Velocity Prediction Program
twa	True Wind Angle
awa	Apparent Wind Angle
awa_{ref}	Reference Apparent Wind Angle
DMG	Distance Made Good

1 INTRODUCTION

The use of Velocity Prediction Programmes, (VPP) to assess yacht performances can be regarded as a well-established technique in yacht design. Considerable improvements were actually carried out in the last decades, in order to achieve a closer modeling of hydrodynamics and aerodynamics of sailing yachts [1]. As a result, designers can now obtain valuable information on the straight-line, equilibrium state of a yacht for each point of sail and wind speed. Screening among a fleet of design candidates is also possible through VPPs: a 'test fleet' can be generated, usually by applying systematic variations to a 'base boat', and the minimum time required to complete a set of racing legs can be predicted. VPPs have also been used in conjunction with weather databases, in order to predict the outcome of races [2]: these are usually identified as Race Modeling Programs (RMPs). It is widely felt that further additions to the traditional models for yacht performance prediction are necessary: as an example, in [3] it is pointed out that aspects of yacht dynamics (namely, the tacking ability) should also be modeled for handicapping purposes. One of the distinctive features of modern yachting is clearly one-design racing: the attention of either yachtsmen, designers, sponsors and media is actually switching to contexts where the skill of crews and the ability to make the right decisions at the right time are keys to winning races. In the Authors' opinion, any improved approach to performance prediction should therefore aim at taking two factors into account: the racing hardware, the boat, and the software (or wetware!), the sailors. Regrettably, little or no published attention has been paid to the latter issue so far. This seems to be paradoxical, since sailing is a discipline so rich in uncertainty that gambling, taking chances, predicting future scenarios, assessing outcomes of decisions always come heavily into play.

2 YACHT PERFORMANCE PREDICTION

2.1 BACKGROUND ON VPPs

The goal of VPPs consists in solving iteratively the equilibrium equations of a sailing yacht subject to hydrodynamic loads (hull and appendages) and aerodynamic loads (sailplan). The steady state surge speed of the yacht can therefore be calculated for a range of wind speeds, points of sail and sail inventories, which then gives designers an insight into the overall quality of their yacht design. The reliability of VPP predictions is closely related to the quality of experimental and numerical data upon which the aero-hydrodynamic models are based. To bear the costs of a close modeling of a sailing yacht, with the purpose of getting accurate VPP predictions, is still far from being an easy task. In fact, access to facilities such as a suitably-sized towing tank and a wind tunnel is required, in order to investigate the hydrodynamic behaviour of appended hulls and to build up the aerodynamic model. A numerical approach in terms of Computational Fluid Dynamics can also be regarded as a valuable source of information, but traditional testing can hardly be avoided, since numerical methods can provide just partial responses to designers.

2.2 DYNAMIC VPPs

Altough further improvements can still be achieved, VPP technology in itself looks mature enough: research is therefore required to take a step forward and investigate unsteady aspects of sailing yacht motion. A few attempts to investigate yacht dynamics in the time-domain can be found in recent literature. Some Authors have focused on manoeuvering, in order to evaluate the optimal tacking procedure [3], [4], while others have simulated a yacht racing on an upwind leg, focusing on its motion in a seaway [5] or its interactions with an opponent [6]. A great part of the Authors concentrate on solving simultaneously the set of unsteady non-linear equations of motions, or the use of system identification, based on neural networks, has been investigated as well. Up to six degrees of freedom (DOFs) have been taken into account, but four DOFs (surge, sway, yaw and roll) analyses proved to be adequate for tacking simulations and yielded results whose agreement with full scale trials is reasonable [4]. Therefore, the latter approach has been followed in this work; the non-linear equations of motions are those proposed by Masayuma et al. [4]. The yacht reference frame adopted here is the horizontal body axes system.

3 FEATURES OF THE SAILING SIMULATION

The four equations of motions mentioned in the above Section represent the core of the sailing simulator described herein, whose purpose is to estimate the time a given yacht takes to sail a racecourse. The simulator is composed of three interacting modules:

- a physical model of an International America's Cup Class (IACC) yacht;
- a visualization module where the yacht motion is shown in a virtual reality context;
- a control module, referred to as *automatic crew*.

The IACC yacht is racing solo, against the clock: this is to show to what extent strategical decisions influence the time required to complete a race. The simulator has been implemented in MATLAB: this choice lead to slower simulation times but, facilitated algorithm development and offered the possibility of interacting with a virtual reality environment, either to model yacht features or to generate animations.

3.1 PHYSICAL MODEL OF THE YACHT

The geometry of an IACC hull referred to as *M566* has been implemented in the present version of the simulator; several towing tank and CFD tests have been carried out on the *M566* model so far [7], and a fairly large amount of data is available on its hydrodynamic resistance, sideforce and manoeuvering characteristics. However, data such as added masses and higher order hydrodynamic derivatives for the *M566* have not been calculated so far; if the investigation pattern suggested in [4] were followed, full-scale trials such as rolling tests with and without sails would be required, which is well beyond the scope of this paper. So, although the experimental results provided in [4] are not referred to an IACC yacht, some of those data are still used herein, since it is thought they provide a sensible starting place for dynamic analyses. A mainsail-jib combination only has been implemented here: geometry and further details on this sail inventory are provided in [8]. Lift and drag sail coefficients (C_L and C_D respectively) expressed as a function of true wind angle are available from past wind tunnel tests on IACC sailplans. When model sails are tested, they are usually trimmed in real-time by means of a remote control: aim of the trimming process is to attain the maximum C_L or maximum C_L/C_D ratio at each apparent wind angle of the test matrix. However, when human sail trimmers are modeled, sub-optimal sail performances should be considered as well (i.e. C_L and C_D for under/overtrimmed sails). A sensible way to account for an ill-trimmed sail could be to express sail lift and drag as a function of sail incidence angle α instead of apparent wind angle (awa): as a full set of data is not available on this, an estimate had to be made for sail coefficients between $\alpha = \pi$, or dead downwind trim, and $\alpha = 2\pi$, when apparent wind hits the sail leech first, then flows towards the luff. This approximation, which is deemed reasonable for the purposes of the present paper, is shown in Figs. 1 and Fig. 2.

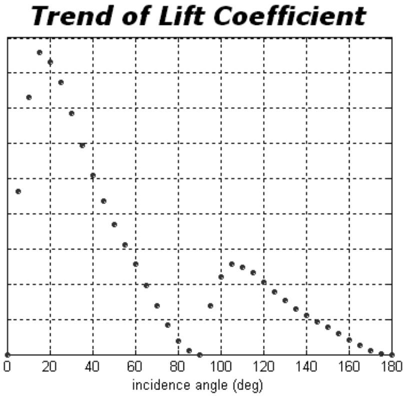

Figure 1: lift coefficient C_L as a function of incidence angle α

3.2 SIMULATION AND VISUALIZATION OF RESULTS

While a simulation is running, a stepwise solution of the four simultaneous equations of motion has to be calculated; a standard fourth order Runge-Kutta solver is used for this purpose. The CPU time required to simulate a one-mile upwind leg in an arbitrary true wind pattern is approximately 60 seconds on a conventional PC. At every time-step, the time-histories of state variables (velocities, accelerations, leeway, yacht heading, apparent wind speed and angle), hydrodynamic and aerodynamic forces, rudder angle and sail trim parameters are recorded. This set of data can be supplied to the visualization routine, programmed within Simulink and using the features of MATLAB Vir-

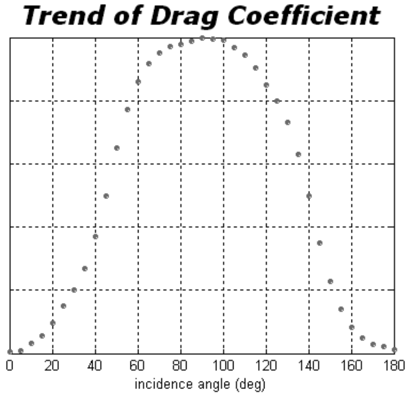

Figure 2: drag coefficient C_D as a function of incidence angle α

tual Reality Toolbox in order to generate "offline" animations. Within this context, the use of Virtual Reality Modeling Language (VRML) allowed both the modelling and animation of the yacht motion within a 3D world. From a physical standpoint, this allows the yacht accelerations and heel, rudder movements, and sail trim to be visualized and compared with actual (recorded) values. In addition, positives and negative aspects of the race strategy implemented by the automatic crew can be highlighted as the simulation proceeds on. With this purpose, a one-design fleet implementing different strategies can sail the same course simultaneously (as in Fig. 3): in this case no mutual interactions occur, so that races can only be won thanks to better technical skills (i.e. driving style, sail trim) and a successful race strategy.

Figure 3: a screenshot of the animation

4 HUMAN FACTOR ISSUES IN SAILING

4.1 SOURCES OF UNCERTAINTY

As in most outdoor sports, sailing is a discipline rich in uncertainty due to ever-changing environmental conditions. One of the keys to winning races is indeed the ability to predict and to *play* effectively all weather changes, namely speed and direction of wind and tide. An extensive analysis on predicting the outcome of match races under weather uncertainty is due to Philpott and Mason [9]: speed and direction of true wind are considered as independent stochastic variables, whose values vary over time and over the racecourse. Changes in wind conditions are supposed to propagate downstream according to Taylor's hypothesis of wind engineering: wind eddies travel down the flow field at a given mean wind speed. The model is based on wind measurements on Hauraki Gulf, New Zealand and can model large shifts in wind direction occurring at random intervals. Other than weather conditions, many more non-deterministic factors affect the outcome of sail races: insight on opponents behaviour, sailors' self-confidence and personal attitude towards risk (risk-averse or risk-taking), knowledge of racing rules being just a few examples. These factors influence both racing strategy and tactics which, in turns, affect the way a yacht is sailed. Other than technical skills, a wide range of additional abilities are therefore required to win races: assess risks connected to decisions, estimate gain/loss probabilities, predict changes to present race scenario, react to unforeseen events. Personal experience, training and recalling similar situations from the past are therefore key skills to winning races.

4.2 SAILORS AS DECISION MAKERS

The factors highlighted above and the role they play in winning or losing races are difficult to quantify and subsequently model within the framework of an automatic yacht crew. However, it is felt that modeling them in general terms can still provide insight to the following questions:

- What drives novices and expert athletes' decisions ?
- How do athletes assess the risk of their decisions ?
- What gains/losses follow sailors' choices ?
- To what extent can athletes predict changes to racing conditions ?
- Can good technical skills (boatspeed) compensate poor decisions and vice-versa?

Behavioural sciences are underpinning many disciplines such as football, cricket and racquet sports and interesting conclusions can be drawn. Regrettably, only a few behavioural investigations on competitive sailing contexts are available. Rulence-Paques et al. [10] claim that athletes' knowledge base is apparently structured and organized in decision-making schemata, whose *quality* is likely to affect performance. Recent research by Arajo et al. [11] also emphasize the relationship between sailing expertise and decision-making skills, by pointing out that experimental evidence exists that 'best sailors function as better decision-makers'.

4.3 DECISION-MAKING IN THE FACE OF UNCERTAINTY

Investigations on decision making have been carried out in a number of fields: from marketing ('how customers choose a product?') to politics ('how voters choose a candidate?'), from warfare to management sciences, from behavioral finance to criminology ('how people decide to commit a crime?'). A decision-making problem under uncertainty, is usually formulated in terms of a decision matrix, whose general features are reported in Table 1

	S_1	S_2	...	S_j	...	S_n
A_1						
A_2						
...						
A_i				$C_{i,j}$		
...						
A_m						

Table 1: Formulation of a Decision Problem

Columns S_j are referred to as *attributes* or *outcomes* and represent the possible states of a variable V; rows Ai are referred to as *alternatives* or *gambles* and represent the choices available to the decision maker. When A_i is the chosen alternative and outcome S_j occurs, the payoff to the decision maker is $C_{i,j}$. When elements of uncertainty are present, a classical approach is usually followed [12] which assumes that individuals are aware of probability information related to outcomes. A probability distribution $\{P_1, P_2, ..., P_n\}$ therefore exists over $\{S_1, S_2, ..., S_n\}$, such that P_j represents the probability that outcome S_j occurs. A great part of such research is based on the maximization of expected utility: deciders are supposed to evaluate an alternative by guessing payoffs and probabilities for all the possible outcomes. Each payoff is then multiplied (weighted) by the corresponding probability and the products are summed, obtaining therefore the expected utility of the choice. When a number of alternatives is available, the one that shows the largest expected value is supposed to be selected. The above decision making strategy is usually referred to as *weighted added*.

4.4 DECIDING HOW TO DECIDE: MaxiMin AND MaxiMax STRATEGIES

When decision-making problems characterized by n-alternatives and m-outcomes are formulated in terms of a payoff matrix, as in Table 1, several methods exist to identify the most advantageous choice. Depending on the information available with respect to the outcomes $\{S_1, S_2, ..., S_n\}$, two categories are usually considered: decision-making under risk and decision-making under ignorance [12]. In the first case, the assumption of probabilistic information about outcomes is supposed to hold: this is to say that deciders are aware of a probability distribution $\{P_1, P_2, ..., P_n\}$ over $\{S_1, S_2, ..., S_n\}$, such that P_j represents the probability that outcome S_j occurs. Firstly, the *expected payoff* of each alternative has to be calculated as follows:

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

(1) can be regarded as a weighted average, where each payoff is weighted by the probability of an outcome to happen. Individuals are then supposed to choose the alternative yielding the highest value of E_i. Conversely, when deciding under ignorance, no probabilistic information is attached to outcomes and the decision maker is supposed to express a judgement according to his *attitude* towards risk. Three prototypical attitudes are usually modeled in literature: a pessimistic/conservative, an optimistic/adventurous and a neutral attitude. In the first case, a strategy referred to as *MaxiMin* is adopted: being afraid of losses, individuals are firstly supposed to consider the minimum payoff for each alternative:

$$EP_i^{(min)} = min_j(C_{i,j}) \tag{2}$$

then choosing the alternative whose $EP_i^{(min)}$ is largest. When modeling an optimistic attitude, the so-called *MaxiMax* strategy is used instead: being confident in winning, individuals are firstly supposed to calculate the maximum payoff for each alternative:

$$EP_i^{(max)} = max_j(C_{i,j}) \tag{3}$$

and eventually choosing the alternative showing the largest $EP_i^{(max)}$. Lastly, the strategy expressing a neutral attitude is based upon the evaluation of the average payoff for each alternative:

$$EP_i^{(av)} = \frac{1}{n} \sum_{j=1}^{n} C_{i,j} \tag{4}$$

then, again, the preferred alternative is the one whose $EP_i^{(av)}$ is largest.

5 SET-UP OF AN AUTOMATIC CREW

An automatic crew system has been implemented that is composed of three sub-systems, organized as shown in 2. The automatic crew has the task of sailing the yacht on a given racecourse, according to a set of basic strategical rules. Details on the sub-systems are provided in the following paragraphs.

5.1 HELMSMAN

An attempt of simulating human actions on a yacht rudder can be found in [5], where a proportional-derivative (PD) controller is adopted that controls the error between the actual and target yacht heading. Weather helm effect is accounted for by applying an open-loop rudder offset

Sub-system	Input	Output
Helmsman	yacht state variables navigator decisions (e.g. target heading when sailing in a straight line)	rudder angle δ rudder rate $d\delta/dt$
Sail Trimmer	yacht state variables navigator decisions (e.g. target sheeting angle)	sheeting angle γ sheeting rate $d\gamma/dt$
Navigator	yacht state variables	decisions

Table 2: Automatic crew system

expressed as a predetermined function of true wind angle (*twa*). The PD controller is switched off while manoeuvering, when rudder position is being supplied as a function of time. Two steering modes have been adopted here, in order to allow the yacht to sail a complete racecourse: a *fixed-awa* mode for upwind and dead downwind legs, when beating is necessary to get to the next mark, and a *fixed-heading* mode for reaching legs, when it is possible to sail to the next mark in a straight line. Both steering fashions are based on simple PID controllers, whose gains have been adjusted in order to mimic actual time-histories of rudder angle. Upwind steering based on the *fixed-awa* PID yields a straightforward, yet effective, model for tacking: the sign of target awa is changed and the PID lets the yacht tack around without exibiting unrealistic overshoots.

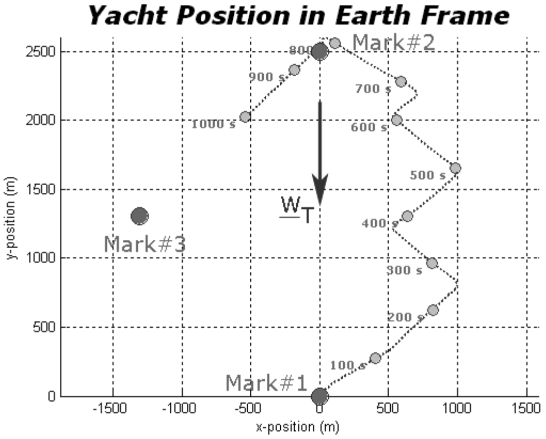

Figure 4: yacht reaching (t=1000s) towards Mark3 at a fixed heading; WT = true wind vector

5.2 SAIL TRIMMER

A mainsail-genoa combination is considered here, whose details can be found in [8]. Two sail trimming modes have been implemented in the simulator: the first one provides directly the sailplan C_L and C_D as a function of awa. Since no human judgement is involved, this can be regarded as the optimal trimming mode. A second trimming mode provides C_L and C_D indirectly: the sail trimmer module takes awa as an input and returns the sheeting angle γ with respect to the yacht centreline. Once γ is known, the sail angle of attack α is calculated out of awa, the yacht leeway β and γ through the formula (5) below, according to Fig. 5

$$\alpha = awa - (\beta + \gamma) \qquad (5)$$

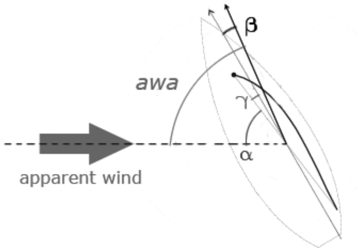

Figure 5: Schematic of reference angles for the yacht

C_L and C_D can then be calculated through lookup tables. Linear $\gamma(awa)$ trimming rules are adopted here: this is to say that sails are eased off as the helmsman bears away, which is a basic sail trim technique. A PID controller has been implemented alongside with the latter sail trim sub-system. The PID is required to take over in strong breezes, when the sailplan is overpowered and sails have to be eased off in order to keep the yacht heel angle within acceptable limits. The choice of such a threshold for the heel angle represents a further aspect open to human judgement.

5.3 NAVIGATOR

This represents the core of the control system and, as in real-life sailing, issues decisions that affect both the steering and sail trimming. Firstly, it checks the yacht position at each time-step of the simulation, detecting as an example when a layline is hit or a mark has to be rounded. Secondly, it detects when the weather conditions change and can issue strategical decisions accordingly (e.g. to tack on a windshift). The navigator sub-system also deals with manoeuvres: for instance, it issues the decision of tacking and detects when the boat has recovered from a tack (attainment of surge speed target value) and the next one can take place. In spite of the basic set of strategic rules implemented so far, broad spaces for simulating human behaviour are present. One example is provided below: Windshifts: when sailing in shifty wind conditions on upwind or dead-downwind legs, considerable advantage can be obtained by sailing on the lifted tack (i.e. the one that yields the higher boatspeed towards the mark). The decision of tacking when a boat is hit by a windshift is not trivial: the shift should be sufficiently large and stable to be worth the time loss of a tack.

6 UPWIND SAILING AND GAMBLING: A CASE STUDY

A common decision making problem arising while sailing upwind is considered in the present section. A yacht is supposed to be headed by a 10° windshift, which generates a strategical dilemma: tacking immediately, delaying the tack or waiting for further changes in the true wind direction. The situation described above is investigated in terms of a decision making problem with three alternatives (actions taken by the crew) and four outcomes (possible developments in the weather scenario). Purpose of the study is to quantify gains and losses following given strategical choices. Furthermore, possible decision-making strategies are suggested, in order to choose among alternatives in a context characterized by uncertainty.

6.1 GENERALITIES

A yacht is supposed to sail on port tack, in a Northerly breeze, in equilibrium conditions and towards the upwind mark. At time t_0 = 200s, the True Wind direction is supposed to shift towards East by 10° (+10° header). The alternatives available are then three (m=3 in Table 1): tacking immediately onto starboard, delaying the tack by 60 seconds or not to tack until further windshifts occur. The navigation stops at t_end = 800s. Four possible weather scenarios or *outcomes* are set (n=4 in Table 1):

1. True Wind Speed and True Wind Angle constant from t_0 = 200s onwards;
2. True Wind shifts further right (additional +10° header) at t_1 = 320s;
3. True Wind shifts back North (-10° lift) at t_1 =320s;
4. True Wind shifts back North (-10° lift), at t_1 =320s, then further left by additional -10° at t_2 =440s;

Choices' payoffs $C_{i,j}$ are calculated according to (6), 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 $j-th$ weather scenario. $DMG*$ is the reference distance sailed in 10 minutes at the initial surge speed $u_0 = u(t=0)$. This yields payoffs within the range [0;1], where higher payoffs correspond to higher levels of *utility*.

$$C_{i,j} = \left(1 - \frac{DMG^* - DMG_{i,j}}{DMG^*}\right) * 100 \qquad (6)$$

After t_0, when the decision is made, the yacht is always sailed according to a unique set of strategical principles: as an 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 decision made at t_0.

6.2 DECISION TABLES

In order to investigate the sensitivity to simulation parameters, two factors are considered: awa_{ref} and tws. Each of them is varied at two levels, yielding four factor combinations: these are due to a 2 (awa_{ref}, 25° and 30°) by 2 (tws, 4m/s and 6m/s) factorial. Payoffs are calculated according to (6), where DMGs were estimated by means of the sailing simulator described in the previous Sections. The case awa_{ref} = 25° and tws = 4m/s is summarized in Tab.3 below; readers are referred to Appendix A for the whole set of payoff matrices.

	S_1	S_2	S_3	S_4
A_1-tack	62.47	72.94	51.77	58.77
A_2-do not tack	34.69	66.67	47.29	55.80
A_3-delay tack	59.88	69.71	48.43	55.45

Table 3: payoff matrix for awa_{ref} = 25° and tws = 4m/s

Before commenting on the simulation results let us consider that, owing to the assumptions described in Sect. 6.1, different scenarios involve different number of tacks. As an example, let us consider scenario S_2 (wind veering to East): if alternative A_1 was selected (dashed line, Fig. 6), the yacht would tack just once (onto starboard) since any subsequent windshift to the right would represent a lift for the starboard tacker, yielding higher VMGs and DMGs. Conversely, if alternative A_2 was chosen (solid line, Fig. 6), the yacht would still be sailing on port 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 headed tack. Now, let us focus on the simulation results of Tab. 3. It can be seen that, when all weather scenarios are equally likely to occur, the most advantageous choice is A_1: tacking as soon as the yacht is headed. Higher payoffs can indeed be obtained when selecting alternative A_1, for any given outcome. Other alternatives (not tacking or delaying the tack) always yield lower payoffs; 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 outcomes instead than across alternatives, i.e. choosing an alternative first and then considering all possible outcomes, it can be observed that highest payoffs are always obtained under the outcome S_2.

6.3 DECISION-MAKING STRATEGIES

Two possible approaches to decision making were highlighted in Sect. 4.4; their application to the present decision-making problem is investigated in the present Section. Let us consider the payoff matrices of Tab. 3 and Appendix A. When hypothesizing a condition of decision-making under ignorance, it can be shown that either an optimistic, a pessimistic and a neutral decider would choose the options of tacking as soon as the yacht is headed (alternative A_1). This is valid irrespectively of the factor combination considered (awa_{ref} and tws). Furthermore, alternative A_3 turns out to be the second-best choice for all factor combinations. This means that, within the four weather scenarios considered, alternative A_1 is the

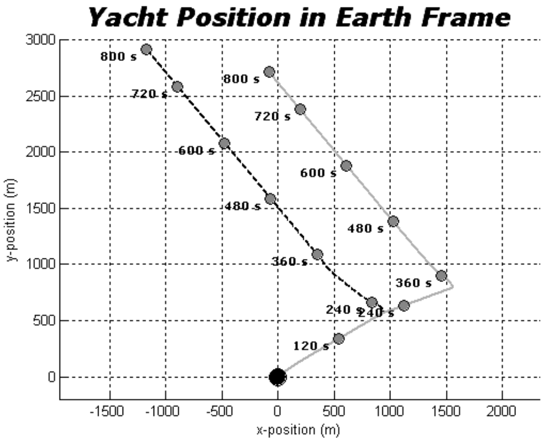

Figure 6: scenario S_2 : dashed line track corresponds to choice A_1, solid line track to choice A_2

choice yielding the highest expected utility and therefore represents the most advantageous strategical option when the evolution of the racing scenario is uncertain. On the other hand, different results can be observed when deciding under risk. As an example, let us consider a possible high-dispersion probability distribution such as $\{P_1, P_2, P_3, P_4\} = \{0.05, 0.12, 0.15, 0.68\}$. In this case, oscillating wind patterns (outcomes S_3 and S_4) are more likely to occur than veering wind patterns (S_1 and S_2): it can be shown that delaying the decision can yield lower payoffs than deciding not to tack. When tws = 6m/s and awa_{ref} = 25°, if outcome S_4 is considered, the yacht that delays the decision sails a 60s beat while headed and pays the price of two tacks (solid track, Fig. 7). Conversely, the yacht that does not tack when hit by the first windshift (t_1 =320s) sails a longer beat while headed, but will not tack afterwards (dashed track, Fig. 7), since it experiences a constant lift after t_2 =440s. Owing to the fact that higher payoffs are weighted by higher probabilities (P_4 = 0.68), alternative A_2 proves to be the second-best choice after A_1.

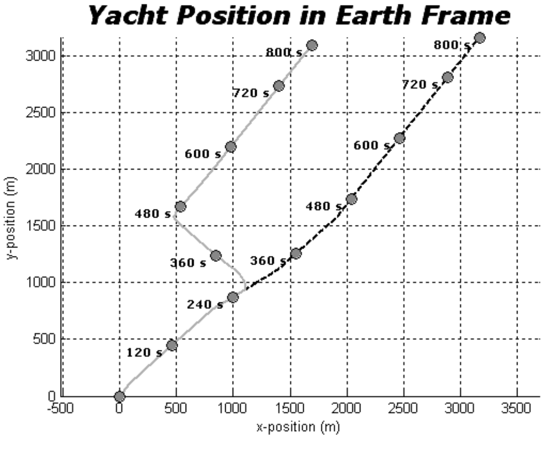

Figure 7: scenario S_4 : dashed line track corresponds to choice A_2, solid line track to choice A_3

7 CONCLUSIONS

A four-DOF dynamic VPP has been developed, making it possible to simulate a yacht racing solo on given racecourses and in predetermined wind patterns. The distinctive feature of the present VPP consists in built-in behavioral models, shaped as an automatic crew. The "crew" is given tasks such as steering the yacht, trimming sails and making strategical decisions, with the purpose of sailing the course efficiently e.g. taking advantage of changes to the weather scenario. The problem of decision-making under uncertainty is addressed and a formulation in terms of payoff matrices is considered. A case study is investigated that involves three strategical alternatives and four possible weather scenarios: gains and losses are assessed through the sailing simulator and payoffs associated with choices are calculated. The most advantageous alternatives is selected through a maximization of expected utility. For this purpose, two possible decision-making contexts are considered: "decision-making under risk" and "under ignorance". In the first case, probabilistic informations associated with outcomes are used, while the latter context involves considerations on the decider 'attitude' towards risk. Further refinements to the model should undoubtedly be carried out in the future: this refers either to a closer modeling of yacht dynamics (e.g. when sharp course changes occur: quick manoeuvres, mark roundings) and to a refinement of the navigation module. In addition, interaction between yachts should be accounted for, so that decision trees related to racing tactics (e.g. blanketing, influence of right of way rules), could be investigated alongside with racing strategy. Nevertheless, several applications can be envisaged for the simulator: as an example, interactive races could be set up and human choices recorded in order to provide a feedback on gains and losses due to personal decision-making schemata.

8 ACKNOWLEDGMENTS

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A PAYOFF MATRICES

	S_1	S_2	S_3	S_4
A_1-tack	80.84	88.92	70.72	76.56
A_2-do not tack	55.19	83.04	66.98	74.54
A_3-delay tack	76.61	84.79	66.40	72.23

Table 4: payoff matrix for awa_{ref} = 25° and tws = 6m/s

	S_1	S_2	S_3	S_4
A_1-tack	42.60	55.16	28.95	37.15
A_2-do not tack	9.67	47.62	24.01	34.25
A_3-delay tack	38.83	51.42	25.16	33.36

Table 5: payoff matrix for awa_{ref} = 30° and tws = 4m/s

	S_1	S_2	S_3	S_4
A_1-tack	69.22	80.38	56.28	63.23
A_2-do not tack	37.97	72.83	52.26	61.94
A_3-delay tack	63.70	74.92	50.73	57.67

Table 6: payoff matrix for awa_{ref} = 30° and tws = 6m/s