INCLUDING HUMAN PERFORMANCE IN THE DYNAMIC MODEL OF A SAILING YACHT: A MATLAB®-SIMULINK® BASED TOOL

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SUMMARY

A sailing simulator is described that takes into account human factors with respect to strategic decisions during a race. Models for yacht-crew interaction have been designed and implemented for the helmsman and the sail tailers, as well as a 'routing engine' that solves problems of a strategical and a tactical nature (e.g. navigation in windshifts, collision avoidance). One or more users can interact with the simulator, so that their behaviour and decision-making process can be recorded, analyzed and compared to that of the automatic crews. The software was implemented in MATLAB-Simulink and consists of two modules: 'Robo-Yacht', for solo and drag races, and 'Robo-Race' for fleet regattas. In the latter case, a real-time animation of the race is delivered to the user in real-time within a virtual reality environment. A series of case studies are presented that demonstrate realistic interactions between a yacht whose decisions are made by a sailor and a mini fleet of autonomous yachts.

NOMENCLATURE

VPP	Velocity Prediction Program
RMP	Race Modelling Program
CFD	Computational Fluid Dynamics
IACC	International America's Cup Class
DSYHS	Delft Systematic Yacht Hull Series
DoF	Degrees of Freedom
tws [twa]	true wind speed [angle]
aws [awa]	apparent wind speed [angle]
u [v]	yacht surge [sway] speed
ψ [φ]	yacht heading [roll] angle
δ [γ]	rudder [sheeting] angle
B	leeway angle
ρ_w	density of water

1. INTRODUCTION

The steady-state performance of a sailing yacht can be predicted with reasonable accuracy and, to some extent, manoeuvring performance can be modelled as well. However, the inclusion of the abilities and skills of the sailors and the assessment of human performance has not been investigated so far.

Building on previous work reported in [1] and [2], a tool has been developed in MATLAB-Simulink where solo races and fleet races are simulated. A four degrees of freedom approach derived by [3] is used as a 'physics engine'. The equations of motion are solved iteratively for each yacht of the fleet and a real-time animation of the race is generated in a virtual reality environment. The crew is modelled in terms of helmsman, sail tailers and a navigator. This approach allows the simulation of different degrees of expertise, either in terms of man-machine interaction (e.g. steering and manoeuvring styles, sail trim) and crew-scenario interaction (opponents, weather, racecourse). Elements of uncertainty and risk due to the environmental conditions are introduced, such as changes in the wind speed and direction.

Three case studies are presented herein, where a small fleet race in a stochastic wind pattern is simulated. In order to do so, aero-hydrodynamic data representative of International America's Cup Class yachts have been considered. Although the yacht features are a constant for the whole fleet, remarkable differences in the overall performance can be observed due to the skills of the crews and the individual judgment of the navigators. Therefore, the overall quality of the crew technique can be assessed, as well as the quality of the race strategy.

2. BACKGROUND TO PERFORMANCE PREDICTION FOR YACHT-CREW SYSTEMS

2.1 VELOCITY PREDICTION PROGRAMS

The most straightforward index of a yacht's performance, at any given point of sail and wind speed, is the forward ('surge') speed in steady sailing conditions. Based on this consideration, the Irving Pratt Project carried out at the MIT in the late Seventies aimed at deriving the surge speed of a yacht based on a limited number of design parameters [4]. One of the deliverables of the Project was a Velocity Prediction Program that represented the foundation of the IMS race handicapping system. The underlying principle of modern VPPs is still the same: to calculate the equilibrium conditions for the yacht by balancing the hydrodynamic and aerodynamic forces exerted on the sails and on the hull, at every wind speed and point of sail.

In order to do so, data on hull hydrostatics, stability, resistance, keel sideforce generation and sail propulsion must be supplied for use by the VPP. Quoting Todter: 'the VPP is the glue that ties all the analysis and test data together' [5]. As a consequence, the quality of a VPP is that of the underlying aero-hydrodynamic models and databases.

The IMS-VPP underwent several revisions: improved models for hull resistance such as those described in [6] were adopted and a closer prediction of downwind sails aerodynamics has been achieved. Readers are referred to [7] for an overview on recent additions to the IMS-VPP. Furthermore, due to the progress in Computational Fluid-Dynamics (CFD), results of numerical simulations can now be used as an input to a VPP with a reasonable degree of confidence [8]. The development of an entirely numerical data based VPP is an alternative to conventional, experiment-based approaches. For example, a tool based on a Reynolds-Averaged Navier Stokes solver for aerodynamic and hydrodynamic forces is described in [9] and, having been validated over three America's Cup cycles, represents the most refined tool to date. As pointed out in the above paper, a RANS-based VPP would offer clear advantages, particularly in the early stages of a new project, when candidate designs are evaluated. However, the complexity of fluid dynamics phenomena involved (unusual appendage configurations, flow separation and reattachment for offwind sails and so forth) require advanced turbulence models, large computational resources and further validation efforts.

2.2 FROM VPPS TO RMPS

Despite the valuable insight provided by a VPP, many non-deterministic variables affect yacht racing, such as weather conditions and sea state. As a consequence, a judgment based on VPP results only is likely to be 'inconclusive and possibly misleading for determining the order of merit of two candidate yachts over a series of races' [10]. Based on the above considerations, weather probabilistic models were coupled with VPPs and referred to as Race Modelling Programs (RMPs). For the 1992 America's Cup, the *Stars and Stripes* design team used a RMP in conjunction with weather and sea state data gathered for over ten years and relative to the race venue in San Diego, USA [5]. The aim of the RMP was to estimate win/loss percentages for a pair of boats engaged in a match-race. Indeed, the RMP results helped in the selection of the best design.

The use of fixed-time increment simulations for comparative evaluation of alternative yacht designs is addressed in [11]. Rather than solving the equations of motion for each candidate, an 'approximate dynamic model' was used that was based on a constant time step and three state variables: position, speed and heel angle. The 'approximate' nature of the model consists in the use of a VPP to evaluate the yacht state at every time step. Stepwise values of the wind speed and wind angle were provided by a weather model tuned on the weather conditions encountered in the Hauraki Gulf, New Zealand. With the aid of the above RMP, win/loss probabilities for any design candidate in a variety of weather conditions could be evaluated.

The studies mentioned above demonstrate that the quality of a design should not be assessed based on steady state performance only. Factors like manoeuvrability, ability to recover speed and ground after tacking, race strategy and tactics have a considerable impact on the time around the course and should therefore be included in race simulations. A few examples of manoeuvring models in the time domain can be found in recent literature. Some Authors have focused on the evaluation of the optimal tacking procedure [12], while others have simulated a yacht racing on an upwind leg, taking into account its motion in a seaway [13] or its interactions with an opponent [14]. Although six degrees of freedom (DOFs) models have been devised, analyses based on four DOFs (surge, sway, yaw and roll) performed well for tacking simulations in calm water and yielded results whose agreement with full scale trials is reasonable [3]. Therefore, the latter approach has been followed in this work . The set of non-linear equations of motion adopted here is that proposed by [3].

3. YACHT-CREW MODEL: DYNAMIC MODEL FOR THE YACHT

The model used herein for the simulation of yacht-crew systems is composed of a dynamic model for the yacht and a collection of models for the 'automatic crew'. Readers are referred to [1] for an overview on the 'physics engine' of the yacht and the solver of the equations of motion. Although the model described in [1] was deemed to be satisfactory for human-in-the-loop investigations, a further refinement has been carried out, namely a calculation of the added mass in sway and added mass moment of inertia in yaw based on regression formulae due to [12]. These issues will be addressed below. Furthermore, an improvement to the sail tailing module has been implemented that is discussed in Section 6.

As mentioned in Section 2, a four DoF model (surge, sway, heel and yaw) devised and validated by Masayuma is being used for the sailing simulations described. The model was built on previous work by Nomoto [15] and was intended to be used for manoeuvring simulations in calm water.

For consistency with [1] and [2], the IACC model 'M566' will be considered in this paper. Both the canoe body and the appendages are typical of yacht designs based on Version 3.0 of the IACC Rule. The 'M566' is used at the University of Southampton for educational purposes and its resistance characteristics have been investigated extensively. Towing tank data and analyses based on VPPs were made available to the Authors. The upright resistance curve for the M566, as supplied to the simulator, is that of Figure 1 below.

Some refinements to the model presented in [1] and [2] were carried out. One of these consisted in a careful evaluation of the added mass in sway and added moment of inertia in yaw. Regression formulae proposed by Keuning[12] and based on the DSYHS were used for this purpose. These are based on the sectional area coefficients for the underwater hull and a correction coefficient (the 'canoe body draught squared') that allows an extension of the formulae to the heeled condition. Such findings were validated by means of 6 DoF forced oscillation tests carried out with the 'Hexamove' rig at Delft University [12].

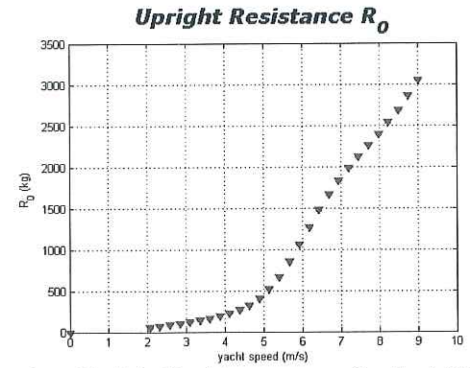

Figure 1: Upright Resistance curve for the M566

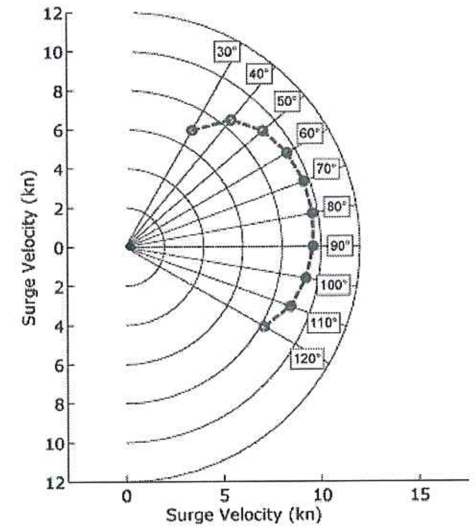

Figure 2: Polars for M566, 10 knots wind speed, white sails

The aerodynamic coefficients used for the simulations (and supplied to the VPP) are those of the standard 'Aerolib' sail inventory used in WinDesign VPP. The latter is a well-established design tool developed by the Wolfson Unit, UK. The 'Aerolib' library includes lift and drag coefficients for individual sails, namely one mainsail, one jib, one spinnaker and one asymmetric spinnaker.

Based on this model, a partial validation of the simulator was carried out, by comparing the yacht polars as predicted by the simulator with those predicted by WinDesign VPP. The comparison of predicted and experimentally derived polars show a good agreement, with a difference of less than 1 knot boatspeed at true wind angles between 30 and 40 degrees at the reference wind speed of 10 knots. This is shown in Figure 2, where a mainsail-jib combination is being considered.

As well as straight line performance, the dynamic model used herein is shown to perform well in predicting the speed and ground losses when tacking and the speed recovery immediately afterwards. A comparison between simulated and full scale tacks is reported in [3], where a close match is achieved for surge speed, heading and heel angle tracks. Just as in the above paper, this investigation has shown a considerable influence of the prescribed rudder angle throughout the tack on the tacking performance itself. This issue will be addressed in Section 6.

4. OVERVIEW ON ROBO-YACHT, A MATLAB® BASED TOOL

MATLAB includes a large number of toolboxes spanning many fields: image processing, system identification, optimization, neural networks being just a few examples. Since the early 1990s the graphical programming language Simulink® has been developed alongside MATLAB, mainly in support of the design of control systems. At present, Simulink is considered as a standard for modelling, simulation and analysis of dynamic systems, with an active community of engineers and academics driving its development, sharing a number of open-source projects and contributing to the enhancement of its capabilities.

4.1 GENERALITIES AND REQUIREMENTS

The MATLAB version of the simulator ('Robo-Yacht') will be presented in the present Section. Built on a physics engine already adopted by [16] and on crew models developed from scratch, this version is intended to:

- simulate solo races and investigate decision-making patterns dealing with race strategy only. This is to say that routing decisions are made based on the race scenario only (marks, wind and weather) without the influence of other yachts.
- investigate the steady-state and the manoeuvering performance of a benchmark yacht and validate the model with the aid of a commercial VPP.
- devise an appropriate model to simulate the behaviour of a virtual crew.

Robo-Yacht can either be used to simulate one race at a time ('SingSim' mode) and for multiple analyses ('MultiSim' mode). The latter option can be used to derive the yacht polar, to carry out sensitivity studies and to perform systematic analyses. For example, test matrices can be set up to explore variations to a base crew (e.g. different tacking styles or race strategy) given a fixed yacht or vice versa.

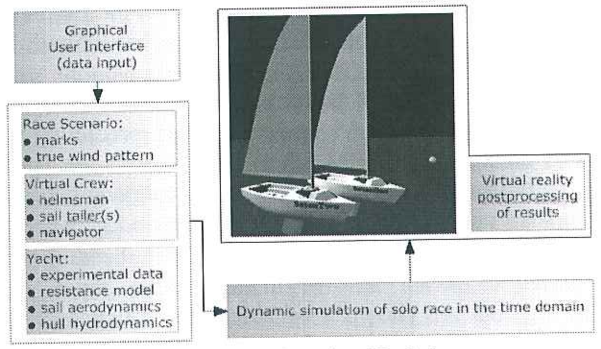

Figure 3: Architecture of 'Robo-Yacht'

4.2 ARCHITECTURE OF ROBO-YACHT

The modules of Robo-Yacht are illustrated in Figure 3. The main features of Robo-Yacht are discussed below, while details on the automatic crew are provided in Section 6.

4.2 (a) Graphical User Interface (GUI)

Prior to launching a simulation, the physics of the modelled yacht-crew system must be loaded into the software, as well as the weather scenario for the race and the features of the racecourse (e.g. number and position of marks). Although default settings are available (those of the IACC M566), these can be partially or entirely replaced by experimental datasets. Both a graphic user interface (GUI) and MATLAB '.mat' data files can be used for this purpose. The latter are organized as multi-level structures, to facilitate the navigation within the dataset. This option has been added so as to carry out the 'MultiSim' analyses mentioned in the previous Section.

A GUI consisting in a series of five consecutive pop-ups is available to the user for setting up and initializing the simulation. The graphical interface was entirely developed in MATLAB®, through the dedicated 'GUIde' tool. The pop-up opening process is based on an intuitive breakdown of the simulator's features:

- Scenario
- Crew
- Hull, appendages and rudder
- Rig and Sails
- Initialization

4.2 (b) Race Scenario

As far as the weather is concerned, papers such as [11] present models for the atmospheric wind profile and its propagation over the race area. It is believed that a good insight into the interactions between a yacht-crew system and the environment of a race can be achieved with less sophisticated wind models than the above. On the other hand, the possibility of simulating elementary patterns for wind speed and angle, according to common classifications found in race strategy manuals such as [17] was of primary importance for the purpose of this paper. Examples of such patterns are: a rhythmically oscillating wind speed (in/out of phase with wind angle) or a dropping/rising wind velocity superimposed to a veering wind speed vector.

A 'Stochastic Wind' option is made available in order to simulate noise superimposed to an arbitrary wind trend. The information on wind speed and angle consisted therefore in deterministic parameters (e.g. period, amplitude and phase) and stochastic features, supplied in terms of variance.

4.2 (c) Simulation engine and run-time issues

While a simulation is running, a solution of the four simultaneous equations of motion has to be calculated for each time step. A standard fourth order Runge-Kutta solver was deemed appropriate for this purpose and an ad-hoc routine was implemented. This numerical method involves four evaluations of the equations of motion per time step, which may slow the simulation down but increases numerical precision. It should be borne in mind that MATLAB is an interpreted programming language, and therefore run-time issues have to be carefully accounted for. However, a satisfactory compromise between accuracy and computational effort could be achieved by using a discrete real time step of 0.2 seconds. Such a time step is normally adopted by other yacht manoeuvring models and has been shown to be adequate for tacking simulation purposes.

The average CPU time required to simulate a one mile upwind leg in an arbitrary true wind pattern is 60 seconds on a conventional workstation with 1Gb RAM. This performance could be further improved by using the MATLAB compiler, which automatically generates low-level code (FORTRAN or C) out of the existing set of m-files. However, this feature has not been explored due to the satisfactory compromise achieved and the later adoption of Simulink for fleet race simulations.

4.2 (d) Virtual Reality module for offline analyses

A Virtual Reality (VR) module has been designed and implemented for post-processing purposes. Once the simulation is complete, an offline animation of the whole race can be run. This has been done in order to explore the 3D modelling and animation capabilities of MATLAB's Virtual Reality Toolbox, as well as to assess the additional computational load. The VR toolbox will be used extensively for fleet race simulations, within the 'Robo-Race' tool.

5. OVERVIEW OF ROBO-RACE

5.1 GENERALITIES AND REQUIREMENTS

During the design and development of 'Robo Yacht', the run-time shortcomings of MATLAB discussed in Section

5.1(a) became evident. For example, the high computational costs of interactive races, with one or more sailors controlling the yachts and receiving a visual feedback on the race in real time, would have slowed down the simulation to a rate much slower than real time. Also, it became clear that sensitivity studies with very large test matrices could not be dealt with efficiently in MATLAB.

A Simulink-based version of Robo-Yacht was therefore implemented, which included some of the existing MATLAB code and made use of the Simulink built-in Runge-Kutta solver for the yacht equations of motion. Also, an improved version of the virtual 3D world for the race simulations was implemented. For example, it was possible to refine the graphics and the level of detail as well as providing real-time visual feedback to the user(s). These issues were of primary importance. In fact, published evidence exists [18] that results of man-in-the-loop sport simulations are unrealistic if the simulation lacks detail (i.e. if the user interacts with an unfamiliar context, his/her judgement is likely to be biased). The Simulink-based tool for fleet race simulations will be referred to as 'Robo-Race'.

5.2 ARCHITECTURE OF ROBO-RACE

In order to simulate virtual races featuring *N* yachts, Robo-Race was designed to include *M* Robo-Yachts (controlled by the simulation engine) and (*N-M*) human controlled yachts. For each Robo-Yacht, the hull, rig and crew parameters are defined when setting up the simulation. This allows the comparison of yacht-crew systems as opposed to compare different yacht designs only.

In order to include the existing Robo-Yacht modules, two possibilities were available: a Simulink-based re-implementation of the model or the inclusion of existing code in Embedded MATLAB (EM) Simulink blocks. EM is essentially a 'low-level' version of the conventional MATLAB language: only a subset of the MATLAB run-time functions is available in EM, so that efficient embeddable C code can be generated. An entirely Simulink-based approach was preferred for frequently called functions (i.e. the equations of motion), while the EM-based approach was used for the automatic crew models.

As well as the yacht-crew architecture, other existing modules were included in Robo-Race, namely the race scenario and the weather module. A rule-based routing strategy already implemented for Robo-Yacht was also used. In Robo-Race, an additional library for automatic crews was implemented, to carry out an efficient race tactics and address conflicts between tactics and strategy (e.g. to tack onto an unfavoured beat to sail in 'clean' air, that is not in the wake of a leading yacht).

5.2 (a) Man-in-the loop features.

In Robo-Race a user can interact with the software by means of a joystick, in order to control a yacht and race against one or more Robo-Yachts. As pointed out earlier in the paper, this feature was implemented to assess the decision-making process driving a race, to compare the strategies of novices with those of experts and, potentially, to feed the results back in the automatic crew model and build expert systems. To date, only rudder controls were made available to the user, in order to focus the investigation on steering strategies. The following options and controls were implemented:

- *Tacking:* when sailing upwind (see *'awa-based'* mode, Section 6.1) a tack can be triggered by clicking a joystick button. The software then performs the tack according to the user-defined technique. Examples of available techniques are reported in Sect. 6.1(a) below.
- *Rudder actions:* when sailing at a given heading (see *'heading-based'* mode, Section 6.1), the yacht heading can be increased/decreased 2 degrees at a time by clicking a joystick button. When in *'awa-based'* mode, the reference apparent wind angle, can be modified in the same way.
- *Viewpoint location:* at every stage of the simulation, the viewpoint on the racing area can be changed by selecting an appropriate camera. A list of available cameras is accessed through a drop-down menu in the simulation window. This issue will be covered in Section 5.2(c).
- *Viewpoint distance:* the extent of the scene displayed in the simulation main window can be adjusted via the joystick throttle. The distance between the *i*-th camera and the origin of the yacht-centered reference frame is considered. The minimum and maximum allowed distances can be set prior to the simulation. This feature is used to investigate how the user's performance is affected by limiting the sailors' overview of the race.


Figure 4: Interactive session of Robo-Race: screens #1 and #2 plus joystick

5.2 (b) Onboard instruments

A number of 'instruments' are available to the user that display information on the yacht state variables (i.e. surge speed, VMG, *awa*, *tws*), conveying therefore an idea on the current performance of the boat. In order to do so, the stepwise values of the state variables were picked up and wired into appropriate ActiveX blocks of the 'Dials and Gauges' Simulink library. These 'onboard instruments' have been collected in a single Simulink window displayed on a separate monitor ('Screen #2', the laptop screen of Figure 4). Screen #2 also displays the tracks of a predefined number of yachts of the fleet, as seen from a camera perpendicular to the sea surface. The tracks are updated in real-time. The main simulation monitor ('Screen #1') displays the animation window as well as the time history of the variables monitored in 'Screen #2'.

5.2 (c) Set-up of Virtual Reality simulations

The design and implementation of VR animations can be performed with the aid of Virtual Reality Modeling Language (VRML) authoring tools, such as V-Realm Builder. The VRML modelling carried out for Robo-Race was composed of eight stages. Stages two and three of the list below were carried out through the open source 3D modeller 'Blender'[19].

- definition of appropriate yacht frames and world frame;
- modelling of the individual yacht components, i.e. hull, appendages, rig and sails in VRML;
- assembly of components, to obtain a VRML model for the IACC yacht;
- texture drawing and draping over the hull/sails surfaces;
- set up and positioning of cameras;
- scene lighting through ambient lights (global, referred to the world frame) and spotlights (local, yacht frame);
- inclusion of a race scenario;
- inclusion of the *N* yachts of the fleet in the 3d world. Each member of the fleet is included as a 'Yacht' node. The arbitrary 'Yacht' node is, in turn, an instance of the generic VRML model of the IACC yacht.

At the end of the VRML modelling, the whole 3D world is available as a single VRML file composed of a 3D scene, cameras, lights and *N* 'Yacht' nodes. Each 'Yacht' node shows several sub-nodes, namely 'Hull', 'Rig', 'Mainsail', 'Headsail', 'Rudder' and 'Wheel'. Nodes and sub-nodes have embedded fields defining for example their position and orientation. These values must be updated by the Robo-Race engine at every time step of the simulation, in order to generate real-time animations. For example, the 'Rudder' sub-node of the *i*-th yacht must expose a 'Rudder.rotation' field to the Robo-Race engine, to be updated at every time step based on the simulation variable 'rudder angle' of the *i*-th yacht.

In order to do so, MATLAB's Virtual Reality toolbox was used as an interface between the VRML environment and Simulink. The 3d world was included in a dedicated Simulink block (or 'VR Sink') where the exposed fields were defined and linked to the corresponding simulation variable.

Great care was taken in the positioning of the cameras within the 3D world. Several pilot simulations with different users showed the importance of varying both the position and the distance of the camera from the scene. The use of five viewpoints and a continuous adjustment of the distance proved to be the best solution to 'navigate' the 3D world efficiently i.e. without losing focus on the navigation when switching viewpoint.

6. YACHT-CREW MODEL: THE AUTOMATIC CREW

An automatic crew has been implemented that is composed of three sub-systems, a helmsman, one or two sail tailers and a navigator. The automatic crew has the task of sailing the yacht on a given racecourse, while minimizing the racing time. A set of basic strategical rules is used for the navigation, in order to take advantage of any changes to the weather scenario. Details on the three sub-systems are provided in the following Sections.

6.1 HELMSMAN

An attempt to simulate the influence of human actions on a yacht rudder can be found in [13], where a proportional-derivative (PD) controller is adopted that responds to the error between the actual and target yacht heading. At any given *twa*, an additional rudder angle is applied, to account for weather helm effects. Several steering modes have been adopted here, in order to allow the yacht to sail an upwind-downwind racecourse: an '*awa-based*' mode for upwind and 'dead downwind' legs, when *beating* is necessary to get to the next mark, and a '*heading-based*' mode for reaching legs, when it is possible to sail to the next mark in a straight line. Both steering techniques are based on Partial Integral Derivative (PID) controllers, whose gains have been adjusted in order to mimic actual time-histories of rudder angle. The reference formulae are Eqns. (3.3) to (3.6) where *awa* and ψ are the process variables, awa_{ref} and ψ_{ref} are the setpoints and the K coefficients are the controller gains. For both PIDs, the output is the commanded rudder angle δ .

$$\delta = K_p(awa - awa_{ref}) + K_i \int e_{awa}(t)dt + K_d \frac{de_{awa}(t)}{dt} \quad (1)$$

$$\delta = K_p(\psi - \psi_{ref}) + K_i \int e_{\psi}(t)dt + K_d \frac{de_{\psi}(t)}{dt} \quad (2)$$

where:

$$e_{awa} - awa - awa_{ref} \quad (3)$$

and

$$e_{\psi} = \psi - \psi_{ref} \quad (4)$$

When used on upwind legs, the '*awa-based*' PID offers a straightforward, yet effective, model for tacking: the sign of target *awa* is changed and the PID lets the yacht tack around without exhibiting unrealistic overshoots.

Both [13] and [3], report studies on tacking techniques that show the considerable influence of the rudder time history across a tack on the overall tacking performance. Therefore, the possibility of switching the controller off when tacking was introduced, and the rudder angle δ was supplied as a function of *awa*.

6.1 (a) Sensitivity studies on helmsman modelling

A systematic analysis was carried out with Robo-Yacht, in order to assess the influence of the rudder angle $\delta(t)$ across a tack. The use of an *awa-based* PID controller ('PID-assisted mode') was compared with the use of prescribed time histories for the rudder ('prescribed δ mode'), in a range of wind speeds. It was found that the PID-based rudder control yielded the best performance in terms of speed recovery, as well as limiting the speed loss. When tacking in 'prescribed δ mode', the use of relatively large rudder angles when coming up proved to be beneficial: limited speed losses were observed and a performance close to that of the PID was achieved. In the latter case, peaks of δ in the region of 60% of the maximum allowed rudder angle were not uncommon. This result is consistent with considerations in [3] where the use of large rudder angles in the first stages of a tack proved to be beneficial.

Wind speeds of 4, 5 and 6 m/s were considered for the present investigations. The gains used for the *awa-based* PID controller were $K_p=1.0$, $K_i=0.01$ and $K_d=0.1$; these derive from a tuning process focused on tacking performance, as well as on accuracy in achieving the prescribed setpoint. Considerations by Harris[20] on avoiding an 'unrealistic' helmsman modelling (e.g. high frequency oscillations for the rudder angle) were also taken into account. In Figure 5, the prescribed rudder angle for the tack is plotted over a *[0;1]* domain, where '0' is the yacht's heading prior to tacking and '1' is the target heading at the end of the manoeuvre (i.e. the heading that corresponds to awa_{ref} for the given wind speed). The tacking simulations were designed in order that a switchover between the 'PID-assisted mode' and the 'prescribed δ mode' would occur automatically, within a given tolerance from the final heading. This tolerance was set to 15°.

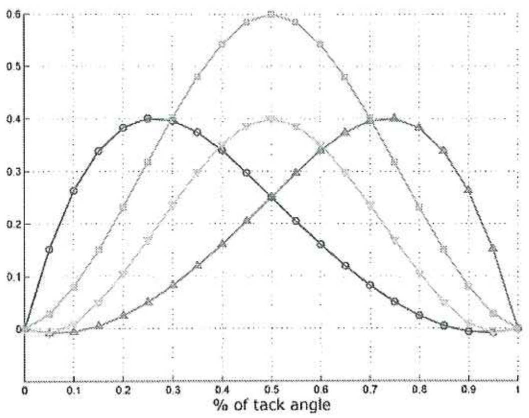

Figure 5: Rudder angle tracks for 'prescribed δ ' mode

The monitored parameters were: u_{start} (surge speed at the beginning of a tack), u_{min} (minimum surge speed across a tack), t_{90} (time interval to recover 90% of u_{start}). Simulation results are plotted in Figure 6 below.

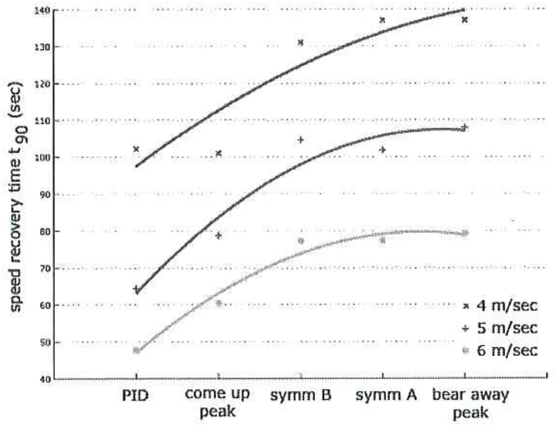

Figure 6: t_{90} for a range of steering models and windspeeds

As mentioned earlier in this Section, the sensitivity study shows that the 'PID-assisted mode' generally yields the faster speed recovery. For the *twa* = 4m/sec case, the 'PID-assisted' tack is as effective as the one controlled by the 'come up peak' steering style. In the latter case, a close matching is observed between the two time histories $\delta(t)$ for a generic tack. The other three models yield similar results and, all in all, show a poor tacking performance.

In conclusion, this sensitivity study shows that the amount of rudder angle used when tacking has a great impact on the 'quality' of the tack itself. This is a further example that using correct models for crew-yacht interaction is crucial for the estimate of the yacht's overall performance. Further case studies in this sense are illustrated in Section 6.2 below.

6.2 SAIL TAILER(S)

Three sail trimming options were implemented in the simulator:

A first option allows the sailplan's C_L and C_D to be returned as a function of *awa*. Just as in a VPP, the coefficients yielding the higher C_L/C_D at the windspeed considered are taken into account.

A second option allows the sailplan's C_L and C_D to be returned as a function of the sheeting angle γ. In order to do so, the sailplan is 'collapsed' into an equivalent mainsail, whose only trimming possibility consists in modifying γ, i.e. the boom angle with respect to the yacht centreline. When this option is activated, a PID controller takes 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, i.e. a setpoint φ_{ref}. The choice of such a threshold for the heel angle represents a further simulation constraint. The above sail trimming models have already been commented on in [2].

A further sail trimming model was implemented in order to simulate the independent trim of the headsail (jib or genoa) and mainsail on upwind legs. The underlying aerodynamic force model is that of the IMS-VPP, originally developed by Hazen [21], that after several revisions can now be considered a 'widespread and robust sail model' [22]. Such a model should take into account sail interaction effects, such as the upwash/downwash of individual sails or the headsail's influence on flow separation over the mainsail, a relevant issue when the flow is guided by the foresail onto the leading edge of the aft sail [23].

Following the IMS-VPP assumptions, a conventional breakdown is used for the sail drag: the total drag coefficient $C_{D,TOTAL}$ is obtained as the sum of parasite drag and induced drag. The parasite drag is composed of a linear component $C_{D,P}$ and a quadratic component, or 'quadratic profile drag'.

Based on the IMS-VPP, the combined effect of two sails can be modelled with a superimposition of the individual sail coefficients of lift and linear parasitic drag, as in Eqns. (5) and (6) below:

$$C_{L,X} = \sum (C_{L,Xi} B_i) w_i \tag{5}$$

$$C_{D,P} = \sum (C_{D,Pi} B_i) w_i \tag{6}$$

$$w_i = {A_i}/{A_{REF}} = {A_i}/{\Sigma A_i} \tag{7}$$

where $i = 1,2$ for the foresail and the main respectively. B_i is a 'blanketing factor' set equal to 1 when sailing upwind, so that no blanketing effects are introduced in the model. The height of the aggregate centre of effort for the sailplan is, again, obtained from those of individual sails. In particular, weighting factors are used which take into account A_i and the individual force coefficients.

The judgment of individual sail tailers is accounted for through the sail trim parameters reef, flat and twist, whose formulation is also derived from the IMS-VPP. The implications of the three coefficients and their influence on the yacht's performance are well documented in [6], [22] and [24]. Suffice it to say that one advantage of an approach based on trim parameters is that sail forces and explicit features of sail trim are 'cleverly avoided' [25].

Based on [4] and [21], *reef* accounts for all crew actions aiming at a reduction of lift through a reduction of sail area. Other actions taken by the crew towards the reduction of lift, such as sail sheeting or adjustments to sail camber, are modelled through the *flat* parameter. Jackson [25] formulates an addition to the IMS-VPP, adopted in 1999, which is based on the *twist* parameter. The effect of *twist* is a reduction in the heeling moment achieved by twisting off (unloading) the head of a sail at the cost of a higher induced drag. A proposal for the additional sail trim parameter *power* (p) is due to Fossati [26].

$$C_{L,TOTAL} = r^2 * f * C_{L,X} \tag{8}$$

$$C_{D,TOTAL} = r^2 C_{D,P} + K_q (r * f * C_{L,X})^2 + \frac{A_{REF} (r * f * C_{L,X})^2}{(\pi H_E{}^2)} \tag{9}$$

Due to the hypothesis of linear superimposition of forces, the aggregate value of 'quadratic parasitic drag' coefficient K_q is the sum of those of the individual sails. $K_q=0.016$ is a reasonably general approximation for a mainsail-jib inventory [27]. The effective rig height H_E is normally taken as 110% of the geometric rig height (masthead) when sailing upwind, drops past 30° *awa* until the value of 100% is achieved in beam reach conditions.

According to Jackson's[25] extension of the IMS-VPP, the vertical position of the centre of effort Z_{CE} is influenced by *r* and *t* and can be obtained from:

$$Z_{CE} = Z_{CE}^{opt} * r * (1 - t) \tag{10}$$

In the present model, tailers' own judgment is modeled in terms of individual trimming response surfaces i.e. *r(awa, aws), f(awa, aws), t(awa, aws)* for each sail.

These functions and correlations among them can be derived from VPPs and refined by simulations and questionnaires/interviews to sailors in order to identify what action are likely to be taken in response to a change in wind speed or angle (e.g. priority given to boatspeed over pointing ability or vice-versa). Artificial Intelligence-based models for sail tailing could be based on neural networks trained with the datasets above.

It should be considered that simulations based on the Monte-Carlo method or driven by a Design of Experiment test matrix are required, owing to the large number of design factors involved. An example of such investigations is provided below.

6.2 (a) Sensitivity studies on sail trim parameters

A sensitivity analysis is set up in order to evaluate the influence of sail trim parameters *reef* (r), *flat* (f) and *twist* (t) over one upwind leg. The test conditions are those of Table 1.

Wind	tws = {3,5,7,9} ± 0.5 m/s, T_{tws}=120s, twa = ± 5 deg, T_{twa}= T_{tws},
Course	*solo race, upwind course, two marks 0.5Nm apart, axis North-South*
Helmsman	*'awa-based' PID, awa_{ref} = 22 deg*
Sail Trim	'dual tailer', test matrix for r,f,t
Navigator	rule-based, set up for tacking on >5deg windshifts

Table 1: Scenario and settings for sensitivity study

Using the 'MultiSim' option of the sailing simulator, a test matrix was set up where both reef and flat were varied over eleven levels (0.5 to 1.0 with .05 increments) for the four windspeeds of Table 1, while the sail twist was kept constant at 1.0. Furthermore, owing to the stochastic nature of the wind speed and angle, a range of variances were explored both for the wind speed and for the wind angle. For each simulation, the initial conditions are the regime values of the yacht state variables for the windspeed concerned. Each race starts at Mark #1 and ends once Mark #2 is about to be rounded on port, that is Mark #2 is seen at amidships by the yacht sailing on the port layline. All results are presented in terms of time around the course.

It should be borne in mind that, being the wind period *T* a constant, the encounter frequency of windshifts is the same at all windspeeds. Therefore a larger number of tacks due to headers is expected at low average windspeeds. So, the effect of sub-optimal combinations of trim parameters (i.e. low boatspeeds) is somewhat 'amplified'.

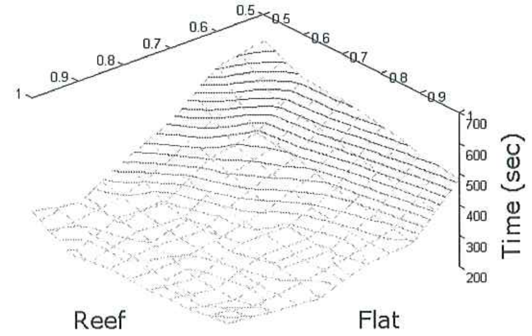

Figure 7: Response surface for RT(r,f) at t = 1.0, tws_{avg} = 7m/s

6.3 NAVIGATOR

6.3 (a) Race strategy.

As in real-life sailing, the navigator issues decisions that have a deep influence on the race outcome. Within the scope of the automatic crew, the navigator checks the yacht position at each time-step of the simulation, detecting for 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, as described below). 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 (through attainment of surge speed target value) and when the next tack needs to take place. A list of the main features implemented by the navigator on is provided below:

- To keep within a given distance from the racecourse axis when sailing upwind. When the lateral boundaries of the racecourse are crossed, the situation is identified as too risky and a tack is called for.
- To tack when an unfavourable windshift (i.e. one that forces the helmsman to bear away in order to keep sailing at a given awa_{ref}) exceeds a given threshold.
- To tack on laylines, i.e. to tack onto any course leading directly to an upwind mark, given the present wind speed and angle.
- To check the boat speed recovery after tacking, forbidding a further tack before a given percentage of the target VMG has been achieved.
- To 'look for' the most advantageous layline (e.g. the port tack layline if marks have to be rounded to port) when approaching an upwind mark. Windshifts are neglected if they would drive the boat away from the chosen layline.
- To sail directly to the upwind mark when the mark itself is within a given distance from the boat. If bearing away is required in order to do so, the '*heading-based*' steering mode is activated and the '*awa-based*' switched off.

Despite the basic set of strategic rules implemented, broad spaces for simulating human behaviour are present. For example, a test case is presented in [1] where a decision-making problem of a strategic nature is investigated by means of a decision matrix. It is shown that the simulator results are consistent with well known principles of race strategy.

6.3 (b) Boat interaction.

An improved version of the navigator was implemented for Robo-Race. As well as race strategy, further issues concerning interactions between two or more boats were addressed. In particular, collision avoidance rules were implemented as well as an elementary model accounting for blanketing effects. Furthermore, a set of parameters regarding the yacht's tactics were monitored and delivered to the user in real time.

As far as the 'right of way' rules are concerned, the Racing Rules of Sailing (RRS) should ideally be implemented to ensure 'fair racing'. However, this task goes well beyond the scope of the present paper, for which a basic set of collision avoidance rules yielded good results. It should be borne in mind that simple situations like port-starboard crossings leave room for individual judgement which is worth addressing when modelling a crew. The latter issue, for example, was addressed by making several options available to the yacht on port (i.e. to tack before the crossing, to 'duck' the starboard tacker, etc.) and tuning the relative parameters in order to reflect the crew skills (i.e. the tack location and the distance from the opponent on starboard).

Simulations by Philpott [11] demonstrated that blanketing models based on weighting factors (rewarding the covering yacht and penalizing the covered yacht) are suitable to model blanketing effects for match race simulations. In the above paper, the physics of covering was modelled in terms of regions of bent air downstream a yacht sailing upwind and turbulence effects downstream a yacht sailing downwind. For the purpose of the interactive simulations presented herein, the precision offered by the above model is deemed satisfactory.

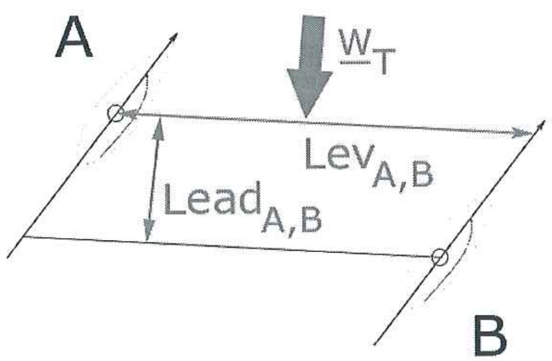

Figure 8: Leverage of yacht B on yacht A, Lead of yacht A on yacht B

Several parameters were monitored throughout the Robo-Races, which are likely to influence the tactical decisions. These can either be delivered to the user in real-time or plotted for post-match analyses. Two examples are the 'leverage' of a yacht B on a yacht A or $Lev_{A,B}(t)$ and the lead of A on B, or $Lead_{A,B}(t)$.

$Lev_{A,B}(t)$ is defined as the distance between A's CG and B's centreline at time t, measured at right angles to the true wind vector $\boldsymbol{W_T}$ (see Figure 8). As explained in [17], the larger the leverage, the higher the gain/loss of ground between boats A and B in the event of a windshift. It should be observed that the above formulation yields non-negative values for $Lev_{A,B}(t)$, with the leverage zeroing only in the event of B's centreline intersecting A's CG.

$Lead_{A,B}(t)$ is defined as the distance between A's CG and B's CG measured parallel to the true wind vector $\mathbf{W_T}$. Questionnaires and interviews with skilled sailors, carried out for research reported in [1] and [2], show that both $Lev_{A,B}(t)$ and $Lead_{A,B}(t)$ influence the tactical choices onboard. For example, a large leverage is regarded as a risky situation and a tactician is likely to call for a tack once a given threshold is exceeded. Conversely, when large leads are observed in match-races, the trailing yacht is likely to build up leverage on the leading yacht in order to gain ground when a favourable windshift (i.e. a header) is expected.

7. TEST CASE: SMALL FLEET RACE

In order to demonstrate the potential of Robo-Race, three test cases are illustrated in this section. In all cases three yachts were involved, whose underlying physical model was that of the 'M566'. The boats, identified with a letter and a colour, were Team A (Blue), Team B (Green) and Team C (Red). Team A was controlled by a user, while Teams B and C were driven by the Robo-Yacht engine. The scope of the simulations is the crossing of a finishing line upwind of a 400m wide starting line. The two lines are 3.2 Nautical Miles (Nm) apart for Test Cases #1 and #2, and 2.1 Nm apart for Test Case #3. Both lines are perpendicular to the wind direction at time $t_0 = 0$. The x-axis of the earthbound frame is coincident with the starting line, while its y-axis lies on the sea surface and is oriented South to North.

In order to focus on the crew performance only, the yacht physics was kept constant while the crew settings were varied as in Tables 2 and 3 below. In all cases, a user was given the partial control of Team A by means of a three axis joystick and a pointing device. The user could control the following:

- current awa_{ref}: variations of $\pm 1°$ at a time were enabled by clicking two joystick buttons.
- tacking: a tack could be triggered by clicking a joystick button .

- zooming on the race area: by moving the joystick cloche backwards (for zooming out) and forwards (for zooming in) in the longitudinal plane of the cloche.
- camera selection: a camera could be selected at any time on a drop-down list in the simulation main window. Nine cameras are available.

A rhythmically oscillating wind pattern was chosen, with *tws* oscillations in phase with those of *twa*. The conditions were $tws = (5 \pm 0.5)$ m/s and $twa \pm 15°$, with the same period of 320s.

7.1 TEST CASE #1.

Test Case #1	*fleet race, upwind course, two marks 3.2Nm apart, axis North-South*		
Team	*A, Blue*	*B,Green (RY)*	*C,Red (RY)*
Helmsman awa_{ref}	user defined	25°	22°
Main Tailer $[r,f,t]_{main}$	[1.0 1.0 1.0]	[0.9 0.9 0.9]	[1.0 1.0 1.0]
Navigator tacks on headers	user defined	≥ 10°	≥ 5°

Table 2: Summary for Test Case #1

In the present test case the user is fully briefed prior to starting about the other Teams and the automatic crew skills. S/he is made aware that Team B will be sailing with sub-optimal crew settings (as detailed in Table 2), while Teams A and C will be sailing with the same sail settings. The user is also informed of the positioning of the fleet at the start. In particular, Team B starts 200m to leeward of A, while Team C starts 200m to windward of A. Team A starts from the origin of the earth reference frame. The whole fleet starts on starboard.

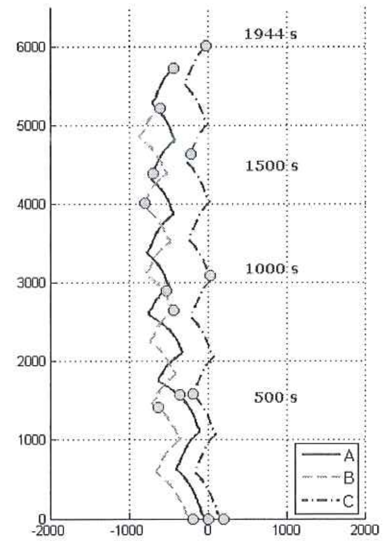

Figure 9: Tracks for Case #1

Tracks from a typical race are shown in Figure 9, while the time history of $Lead_{AB}(t)$ is that of Figure 10. As shown by the tracks, the race can be divided in two parts: in the first one (t = 0 to 500s circa) the tacks of A and B are in phase, since the only way for A to build up $Lead_{AB}$ is to take advantage of windshifts, while B is losing ground due to the poor crew settings. In the second part of the race, where values of $Lead_{AB}$ in excess of 100m can be observed, A only keeps a loose cover on B (by sailing almost parallel and to windward of B that is, in between the opponent and the finishing line).

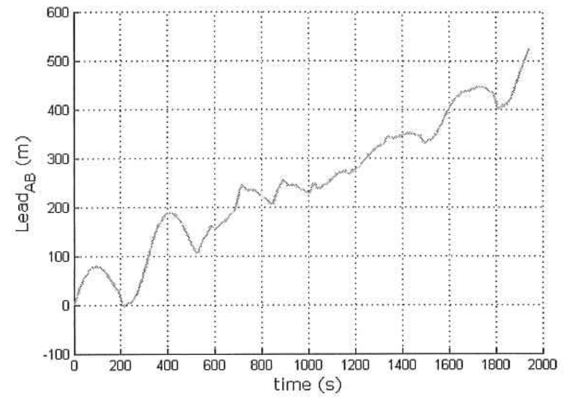

Figure 10: $Lead_{AB}(t)$ for Case #1

7.2 TEST CASE #2.

The settings of Table 2 and the oscillating wind profile defined in Section 7.1 are used in this test case as well. However, although informed of the positioning of the fleet at the start, the user is unaware of the skills of other Teams. This test case was set up to evaluate the behaviour of users provided with partial information only.

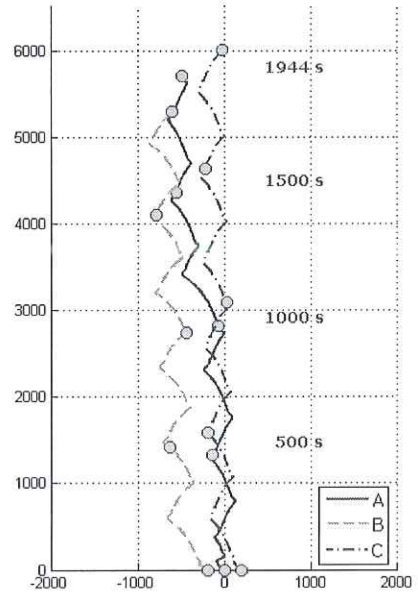

Figure 11: Tracks for Case #2

Tracks from a typical race are shown in Figure 11, while the time history of $Lead_{AB}(t)$ is shown in Figure 12. Just as in the previous case, the race shows a switch in the user's behaviour. At the beginning of the race, the decision to get to windward of the fleet is made.

However, the two consecutive tacks of Team A yield a substantial loss of ground and the decision to follow the nearest opponent is made (*t = 0 to 1000s* circa). The user realized that the wind exhibited a rhythmic pattern and caught up on the fleet by taking advantage of the windshifts, placing tacks at every 3° headers circa. Once confident about the strategy, the user aimed at reducing the lateral separation from Team B, skipping one windshift and sailing to the left of the race area. Then, Team A tacked twice (1200s and 1500s) almost in front of Team B, so as to zero the leverage and consolidate the lead. Finally, a conservative, loose cover on B (similarly to Test Case #1) was chosen, that yielded a slow but steady increase of $Lead_{AB}$ up to 400m, while keeping Lev_{BA} below a 200 m threshold .

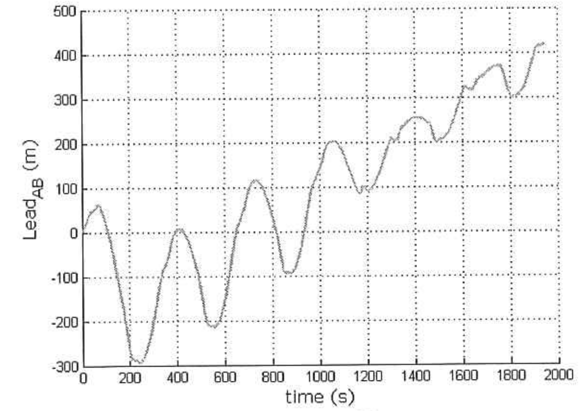

Figure 12: Lead$_{AB}$(t) for Case #2

7.3 TEST CASE #3.

Test Case #3	*fleet race, upwind course, two marks 2.1Nm apart, axis North-South*		
Team	*A, Blue*	*B,Green (RY)*	*C,Red (RY)*
Helmsman *awa_{ref}*	user defined	22°	22°
Main Tailer *$[r,f,t]_{main}$*	[1.0 1.0 1.0]	[1.0 1.0 1.0]	[1.0 1.0 1.0]
Jib Tailer *$[r,f,t]_{jib}$*	[1.0 1.0 1.0]	[1.0 1.0 1.0]	[1.0 1.0 1.0]
Navigator *tacks on headers*	user defined	≥ 5°	≥ 5°

Table 3: Summary for Test Case #2

The settings of Table 3 and the oscillating wind profile defined in Section 7.1 are used for this Test Case. The length of the upwind leg is 2/3 shorter than in the previous test cases. Team B starts 200m to leeward of C, while Team A starts 200m to windward of A. Team C starts from the origin of the earth reference frame. Both Teams B and C are starting on starboard, while Team A starts on port and to windward of the other boats. As opposed to Test Cases #1 and #2, the user was neither informed of the positioning of the fleet on the starting line, nor of the initial tack all three boats were sailing on. This test case was actually centred on the ability of a user to deal with two opponents at a time, when both of them have optimal crew settings.

Tracks from a typical race are shown in Figure 13. As the wind firstly shifts to the left, Teams B and C automatically react by tacking onto starboard and Team A is therefore given a strategic and tactical advantage. However such an advantage could be used in several ways, for example by tacking immediately and, based on the right of way rules, forcing the opponents to tack or duck. Figure 13 shows another option: delaying the tack until the next header. As a consequence, the lead gained by Team A at the start is used between t_1=200s and t_2=450s, when the beat on starboard is extended and a crossing ahead of Team C can be seen. Then, a tight cover on the latter was used (at t =500s) to increase the lead. Further on in the race, the same pattern was followed in order to cross ahead of Team B: the beat on starboard is extended, then a tight cover on B is used (t_3 = 700s) in order to blanket B and then slow it down. It can be seen (for example at t_4 = 1000) that the chosen technique of covering consisted in tacking ahead of one yacht, while keeping parallel and to windward of the other one. From t_4 on, the race is based on taking advantage of the shifts while keeping in control of the other yachts.

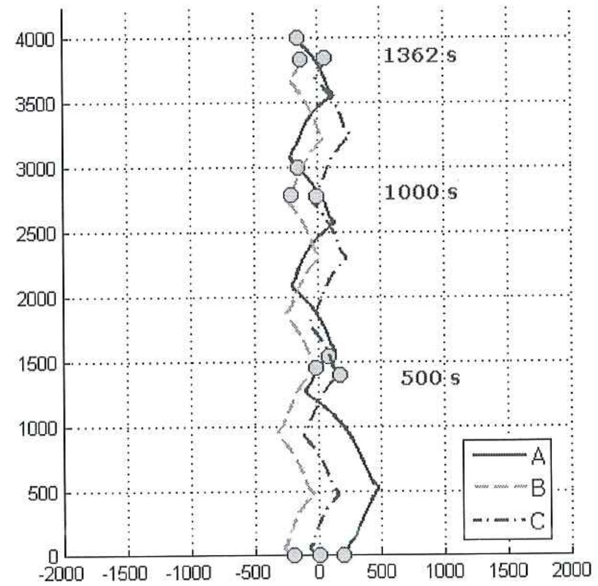

Figure 13: Tracks for Case #3

8. CONCLUSIONS

The development of detailed yacht race simulation that can systematically include the effects of tactical decisions made by the crew has been described. This simulation is demonstrated to be capable of capturing such effects through a series of three case studies that race a fleet of three one-design IACC yachts with one yacht controlled by a real sailor. It has shown that suitable PID based control algorithms are required to provide realistic 4 DoF yacht simulations, of especial importance is the means by which the rudder is controlled through a tack. Previous work used a Matlab based simulation which was unable to run multiple race simulations in real time. It has been demonstrated that real-time fleet races can now be carried out on a standard workstation.

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HYDRO-IMPACT AND FLUID STRUCTURE INTERACTION OF RACING YACHT

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SUMMARY

The hydro-impact phenomenon caused by slamming on sailing yachts and the local structure's response is studied experimentally and numerically. Pressure transducers and a special measurement system named S*lam Patch* has been designed and implemented to measure the hydro-impact pressure and/or local structure's response. The measurement systems are installed on 1/7-scaled model of Open 60 yacht. Modal, rotational drop and seakeeping-slamming tests are carried out. The measured hydro-impact pressure is processed statistically. A methodology to scale up the test result to prototype is mentioned. At the same time, the transient response of simple clamped beam under half-sine impulse is calculated using commercial FEM program to study the effect of the relativity between impulse duration and natural frequency of beam.

NOMENCLATURE

λ	Geometric scale factor
f_n	Natural Frequency
FSI	Fluid-Structure Interaction
FRF	Frequency Response Function
Hydro-impact	Hydrodynamic impact
P/T	Pressure Transducer
RAO	Response Amplitude Operator
S/P	Slam Patch

1 INTRODUCTION

The weight is governing factor for the speed of a racing yacht. To maximise the speed to win a race, optimisation of the structure is the key as to whether the race area is calm water like America's cup or severe sea of Southern Ocean as in Vendée globe or Volvo Ocean Race. Though the speed of the boats increases by the usage of light and stiff material, structural damage by slamming is still significant. It is expected that the structural damage may be influenced by global hydroelastic behaviour by waves and/or local hydro-impact by slamming. In this study, impact of the waves during slamming is the subject of the research.

Firstly, a specially built measurement system named *Slam Patch* (S/P) is designed and implemented with pressure transducers (P/T) on model boat and a series of hydro-impact tests is carried out. This S/P system, which is based on the transmissibility of force, is designed to represent the local structure of boat and/or a simple pressure/force transducer as a transition device in-between P/T and strain gauge. It is found that the S/P system can be implemented to measure the total response of local structure which can be divided into two components – hydro-impact load and vibration behaviour of local structure under fluid structure interaction (FSI).

Secondly, various measurement systems are installed in the model of an Open 60 and hydro-impact tests are carried out - rotational drop test and seakeeping-slamming test. In the drop test, it is found that as drop height increased, which means impact velocity increases, the transient response of structure is significant which far exceeds the magnitude of hydro-impact load itself measured at P/T because of the existence of resonance of structure. In the seakeeping-slamming test, because of the limitation of wave height, a maximum 0.2m waves in model scale is used to find the hydro-impact load. It is found that in 0.2m wave height, the measured response of the S/P system is pure hydro-impact load or very slightly coupled with the structure's resonance. The measured signals are approached statistically to predict the general trend of the hydro-impact phenomenon.

Thirdly, a half sine impulse is applied to a clamped beam and calculation is carried out to see the transient responses of the beam and to establish *Relativity* between the impulse and structure.

2. DESIGN OF S/P SYSTEM

Various instruments – P/T, pressure panel and strain gauge, can measure the hydro-impact load. Each instrument has merits and demerits. For example, P/T can measure exact pressure at a given point but can miss the highest-pressure value. The strain gauge can measure the total response of structure when the structure impacts on fluid but the hydro-impact load by fluid cannot be extracted when the exact response of the structure is unknown.

The concept of the S/P system is to measure the impact load by fluid *and/or* to measure the response of a structure. To design the system, the duration of hydro-impact by slamming must be known, so the components of pure hydro-impact load and response of structure can be separated or coupled.

In the study of Manganelli et al [1], a S/P system is configured to find out the hydro-impact load and hydroelastic effect. In their study, the S/P system is assumed as a 1-DOF system. The 80 by 80mm S/P is designed and tested in dry and wet modes. It is found that, in dry mode, the linear range before the first