DEVELOPMENT OF AN AMERICA'S CUP 45 TACKING SIMULATOR

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This paper describes the development of an AC45 simulator conducted as a student Master's project at the University of Southampton. The main aim was to be able to asses and improve the tacking skills of the helm and the crew through systematic training. The physical interface of the simulator replicates the seating position of the helmsman and the main trimmer and the graphical representation provides the users with visual cues of the simulated boat, boundaries and marks for a sample race course. The theoretical model uses hydrodynamic manoeuvring coefficients based on empirical formulae and experimental data. The aerodynamic forces are pre-calculated using a full-scale RANS CFD simulation. The accuracy of the model is verified against the AC45 racing tracking data to ensure that the speed loss during a tack, experienced by the users of the simulator, is as close to reality as possible. The ultimate aim of the project was to study the potential of the simulator to assess and train the crews, improving their skill in tacking the boat effectively. This has been done by examining the performance of two groups of users over a series of practice sessions. The simulator could be potentially used for training the helmsmen of the Youth America's Cup Red-Bull teams, which have limited budgets, training days and sailing experience compared to the professional AC sailors.

1 INTRODUCTION

The design and construction of high speed sailing catamarans is going through a very innovative period. Since the last monohull America's cup, in 2007, a large number of them have been built. These boats have the power to attract media interest because of their speed and athletic skills required by the crew.

Since 2007 one of the most prominent America's Cup teams, BMW Oracle, has developed the 90-foot trimaran that won the 2010 cup. Following that, the AC45 and the AC72 class boats have been designed and built. Approaching the next event (to be held in September 2013 in San Francisco Bay) it is important to acquire the expertise needed to sail the catamarans in the fastest way without damaging them. In order to compete at high level, a catamaran needs to tack in the most efficient manner. Such a manoeuvre involves a change in heading through the wind. During a tack, a catamaran loses a large part of its speed due to immersion of the flying hull and the associated increase in drag, the aerodynamic forces opposing its forward motion and inability to retain momentum due to lightweight construction. The present project aims to investigate, through the use of a dynamic velocity prediction program (VPP), the possibilities of a tacking manoeuvre training course for the helm and main sheet trimmer, focusing on an AC45 class boat. It was chosen over the AC72 because it is a monotype, meaning that all the catamarans sailing the America's Cup World Series are the same. This would make it viable for the simulator to be used by all the teams and youth squads alike. Another reason of having chosen the AC45 is that live tracking data is available to be downloaded from the ACWS (America's Cup World Series) web site, [1]. This data presents the race conditions and the boat speeds while racing, hence providing a useful validation tool.

The most characteristic feature of the AC45 is its wing-sails. This not only generates more lift while sailing, but also permits to sail closer to the wind, than a conventional sail. Wing sails have better trimming capability than standard soft sails, as the sheeting angle, camber and twist may be adjusted. In order to set the sail, the trimmer needs to adjust a series of sheets and control lines. Therefore, the crew can be trained with a simulator in order to practice the movements they need to perform and to regulate the sail accordingly to the boat state experienced. Nevertheless, the training of the helm in a simulator is more difficult, as the virtual environment should represent the actual race condition closely, taking into account the varying wind intensity, wave direction and height, cloud shapes and all other variables that may be encountered during a race. The real environment needs to be represented not only visually, but also through the physical interface to promote the user sensation of the boat motions.

Sailing simulators have been used in previous works for the analysis of tacking [2, 3], the starting manoeuvre [4], match racing [5], handicap assessment [6, 7], and evaluation of elite athletes [8]. Most of the past work related to sailing simulators carried out at the University of Southampton has investigated the yacht-crew interaction and the possibility to improve the tactical steering and sail trim [9, 10]. One-design races stress the attention on the crew making the right decision at the correct time, so the abilities of the AC45 helm are the key of winning the races.

Furthermore, flight [11], high speed craft [12] and F1 simulators [13] have been widely used to assess the performances of the users and to improve their skills where the expense and or danger are prohibitive to the using the real vehicle. This encourages the application of similar technology in sailing.

2 METHODOLOGY

The project was split up into four main areas: interfacing with the user and modelling of the underlying physics which included the overall simulation framework development and an extensive CFD analysis of the boat's aerodynamics. These are discussed in the following section of this paper. The overview of the established simulator framework is presented as Figure1.

2.1 USER INTERFACE

One of the main deliverables of this project was a physical interface that would integrate effectively with the computational physics engine and the visual interface. This partnership was to increase the realism of the user experience and hence improve the training capability of the simulator. The aim of this part of the project was to facilitate positions for the helm and the main trimmer who would have to closely cooperate in the exercises carried out, much as on the real boat.

The concept of creating a moving structure that would represent the motions of the boat was rejected due to time, budget and space limitations. A static main structure was hence designed and built.

Substantial amount of care was taken to make use of anthropometric data to ensure that the users' position would reflect what they would experience in real life, hence improving the realism greatly [8], [14, 15, 16]. It was decided that a hiking position, while using the physical interface, would be encouraged through designing a bench that simulates a heeled hull surface and by providing a set of toe straps. Information was gained on creating a suitable hiking configuration through analysis of the currently available hiking bench products.

Due to space limitations the physical interface had to be dimensioned in such way as to make effective use of an average size room which was available for the testing. The main material used was aluminium, given its small density and the implied portability of the simulator. This was further encouraged by applying a modular design with no permanent connections.

Two actuators were required, one to represent the tiller and one to act as the wing sail sheet. USB game controllers were used because of its advantages such as compatibility with MATLAB® Simulink®, minimal electrical engineering required and the low cost compared with creating an actuator from the ground up. It was aimed to enable the controllers to transmit force to the users and hence give them invaluable cues as to the state of the boat.

For the rudder, the chosen game controller was the Microsoft Force Feedback 2 Joystick. Its setup required minimal effort in the conversion of the primary joystick axis to the tiller axis. Two motors controlling the x and y axes were connected to a PCB holding the processing unit in order to increase the magnitude of the generated torque. By default, each motor was fitted with a rotary potentiometer which was used to transmit the angular rudder displacement to the simulator. It has been discovered during the testing that mainly due to numerical reasons high-frequency oscillations would be fed to the users. These were commented on as very disturbing and blurring the actual response of the boat. A digital low-pass filter was therefore implemented.

The main sheet actuator was made up of a Microsoft force feedback steering wheel. As the wheel is rotated it responds with a torque and creates tension in the mainsheet. As well as providing a force to resist the user sheeting in it also reels the main sheet back inside once the user force is removed.

A set of mock-ups was built in the process and the input of a range of potential users was factorised into the design process. The finalised concept design is presented as Figure 2.

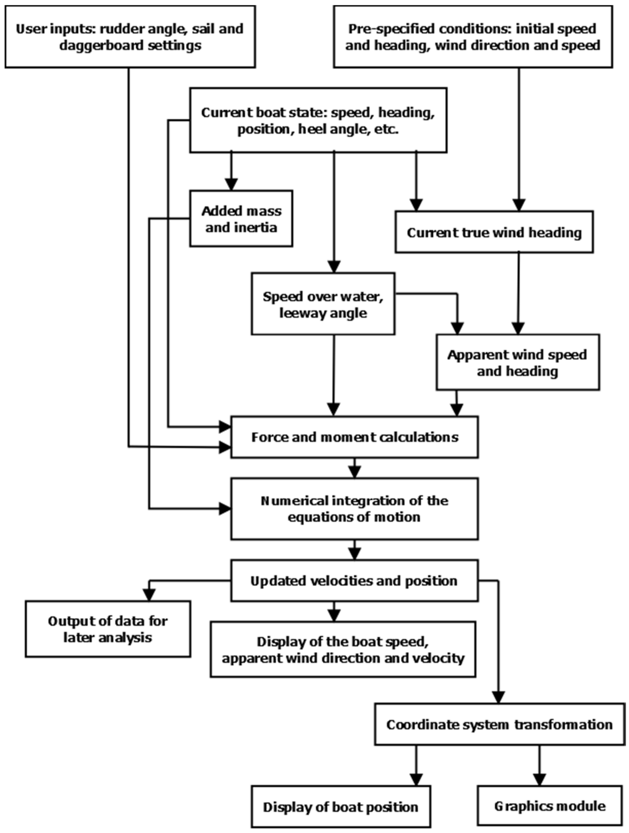

Figure 1: Overview of the simulator framework.

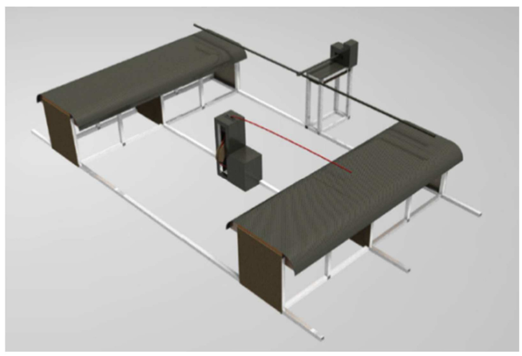

Figure 2: Final concept design of the actuators and seating positions for the crew.

To complement the physical actuators and provide the user with the necessary information about the boat condition a graphical user interface was included in the overall system. This was displayed and used via a 10" touchscreen monitor. One of the main purposes of this was to serve as an external control tool used by the main trimmer in order to control the twist in the wing, the flatness of the jib and the position of the daggerboards. Secondly, it would display the boat speed, the wind speed and direction, as well as a chart plotter with the boat position indicated with respect to ACWS race courses. This aimed to aid in the navigation and to allow full control over the boat to be executed. A sample of the interface window can be seen in Figure 3.

STANAG 3869 AI aircraft ergonomics guideline and ISO standards (DIN EN ISO 9241-3) were followed in order to determine a suitable layout and formatting for the interface [17, 18].

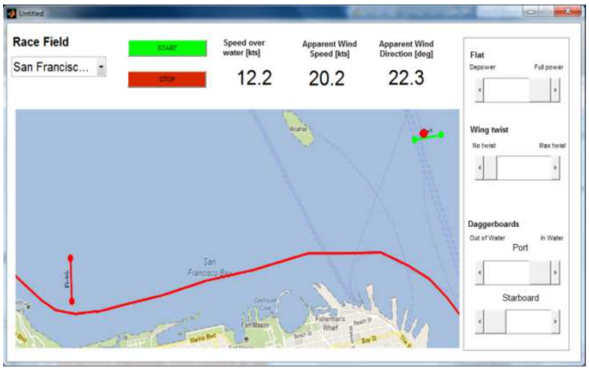

Figure 3: Screen shot of the touschscreen user interface used for control of the boat and information transfer to the users.

2.2 PHYSICS MODELLING

The principle idea behind a real-time simulation of a yacht revolves around constructing a set of equations of motion describing each of the degrees of freedom. For sailing yachts the model originally presented by Masuyama et. al. in 1995 is the most prevalent across the literature [2], [6], [9, 10], [14], [19]. It was used in this project given that it has been widely tested and became an industry standard of describing dynamic sailboat motions. The full set of equations of motion used can be written as:

$$(m+m_x)\ddot{x}-(m+m_y cos^2(\phi)+m_z sin^2(\phi))\dot{y}\dot{\psi} = X_0+X_H+X_{\dot{y}\dot{\psi}}\dot{y}\dot{\psi}+X_R+X_S$$

$$(m+m_y cos^2(\phi)+m_z sin^2(\phi))\ddot{y}+(m+m_x)\dot{x}\dot{\phi} +2(m_z-m_y)sin(\phi)cos(\phi)\dot{y}\dot{\phi} = Y_H+Y_{\dot{\phi}}\dot{\phi}+Y_{\dot{\psi}}\dot{\psi}+Y_R+Y_S$$

$$(I_{xx}+J_{xx})\ddot{\phi}-[(I_{yy}+J_{yy})-(I_{zz}+J_{zz})]sin(\phi)cos(\phi)\dot{\psi}^2 = K_H+K_{\dot{\phi}}\dot{\phi}+K_R+K_S-mg\bar{GM}sin(\phi)$$

$$(Iyy+J_{yy})sin^2(\phi)+(I_{zz}+J_{zz})cos^2(\phi)\ddot{\psi}+2[(I_{yy}+J_{yy}) -(I_{zz}+Jzz)]sin(\phi)cos(\phi)\dot{\psi} = N_H+N_{\dot{\psi}}\dot{\psi}+N_R+N_S$$

A substantial amount of consideration has been given to whether the pitch and heave motions should be ignored in the physics engine. Including these would allow pitch-poling to be examined, more realistic hydrodynamic drag values could also be calculated. However, the primary aim of the project was to simulate the upwind condition where pitch-poling is not an issue. Furthermore, the regattas are sailed in enclosed bays, where the waves encountered are relatively small. Also, the effort and amount of analysis required to introduce and validate a full six degree of freedom model were beyond the scope of this project. Hence it has been decided to exclude the heave and pitch motions from the simulation.

The differential equations governing the motion can be integrated with respect to time twice, given a set of initial conditions, in order to yield the velocity and displacement in each of the degrees of freedom. The most commonly used numerical integration scheme adopted for sailing yacht simulation is a fixed-step Runge-Kutta 4th order method which was used for the purpose of this project with a fixed time-step of 0.1 seconds. It has been found that reducing it does not yield any noticeable improvement in the quality of the solution obtained but may slow the simulation down significantly.

An important task was to accurately estimate the mass and inertias of the boat. Some of these were calculated using the 3D model and mass properties of each of the AC45 principle elements. The added masses and inertias were calculated using potential flow, assuming the hull is a very high aspect-ratio ellipsoid. It is recommended, however, to use more detailed estimates as early as possible in the future if sufficient data is available.

The flow speed experienced by the appendages and sails will be affected by the roll and yaw motions of the boat. The magnitude of this effect was estimated by calculating the local velocity due to turning motion a distance away from the axis of rotation and including it in the apparent wind or appendage inflow velocity computation in a vector form. For the adopted approach this was done at the centre of effort of each lifting element.

In a dynamic VPP it is important to account for the unsteady effects, such as lift or drag coefficient changes. However, this was quite challenging for this application as it was never known a priori when the user will execute a manoeuvre and whether it will end in a tack or just a change of course and hence most known empirical formulae could not be adopted [20]. It was therefore decided to only account for the dynamic effects by considering the flow velocity variations.

No towing tank data was available for the AC45 boat. For this reason an empirical formulation of the Southampton NPL series was used to calculate the wavemaking drag, which was complemented by the standard ITTC '57 friction line to account for the viscous drag [21]. Given the shallow draught of the boat the sideforce generated by the hull was neglected.

It was decided to use the semi-empirical formulae presented by [22] to determine the forces acting on the appendages as they were thought to be easy to implement, robust and widely accepted for their accuracy. Torque on the rudder stock was also calculated in order to provide force feedback to the user, as discussed earlier in the paper.

In order to determine the forces acting on the headsail the data presented by the ORC for implementation in steady-state VPP was used [23] as this has been widely recognised as a high-quality source.

The most challenging part of describing the physics of an AC45 class boat was dealing with the forces generated by the wing sail. This was done based on an extensive CFD study described later in this paper.

It is worth noting that wind speed and direction fluctuations are present in the real environment. In practice, this has a significant effect on the performance of the sails and requires constant attention of the crew in terms of trimming the sails for optimum performance. Multiple ways of describing this phenomenon mathematically exist, typically by employing a combined set of sinusoidal functions and by introducing an element of randomness. This was not implemented in the current simulator because of the possibility that the additional fluctuations will slow down the development of the force feedback effects and blur other phenomena taking place.

At the initial development stage it has been discovered that the physics model is prone to oscillations in roll. This was believed to have originated from accounting for hydrodynamic damping components insufficiently (at that time the only damping terms present were provided by the varying inflow speeds and angles as a result of the roll motion which translated into a damping force). It has been suggested that an additional damping term would exist due to the fact that the windward hull penetrates the water surface when the heel angle varies. As a result, the GZ arm changes but also a moment proportional to the demihull heave damping force is imposed on the entire boat system. As the physics model was being refined at a later stage this component was accounted for by calculating the heave damping using strip theory based on the solution for Lewis sections.

2.3 WING SAIL CFD ANALYSIS

The AC45 boats are characterised by a symmetric wing sail consisting of a main wing rotating about the mast and three rear flaps rotating at 90% of the chord of the forward wing, able to produce lift on both tacks. The approach was to obtain the aerodynamic forces and moments acting on the wing in an upwind sailing condition and then implement the results in the physics engine via interpolation.

In order to accurately predict the boat speed during a tack, the available tracking data from the America's Cup series races were analysed. From this data it was possible to extract the sailing conditions of the catamarans (i.e. average wind speed, apparent wind angle and the corresponding boat speed). A test matrix for the CFD analysis was then completed by analysing five different parameters (i.e. apparent wind speed "VA", apparent wind angle "AWA", heel angle "φ", wing sheeting angle "δ_1", flap sheeting angles "$\delta 2_1$", "$\delta 2_2$" and "$\delta 2_3$", where the subscripts 1, 2 and 3 represent the bottom. Middle and top flap respectively) and focusing on upwind sailing as only the tacking manoeuvre was analysed.

The flow was modelled to be turbulent as the wing sail is affected by the presence of the free surface boundary layer and the relatively slow speed enhances the turbulence interactions between the wind and the sail. The surface roughness of the sea, constituting the bottom surface of the domain, was also modelled as it affects the wind shear profile.

Multiple cases were solved using ANSYS CFX. However, some verification simulations were run in OpenFOAM using the North Sails software, previously used by the Wolfson Unit for Marine Technology and Industrial Aerodynamics (WUMTIA) to calculate the aerodynamic performance of the AC45 and AC72.

The geometry of the wing sail was modelled to be placed at the centre of the domain, with the frame of reference at the free-surface below the centre of rotation of the forward wing. It was then necessary to assess the upwind sheeting angle variation. Based on consultations with Youth America's Cup sailors these were set as $\delta_{WING,1} \pm 20 - 30°$(forward wing camber), $\delta_{WING,2} \pm 10 - 30°$ (rear wing camber with respect to the forward wing) and the twist angle $\pm 2 - 5°$.

An unstructured mesh was created and a mesh refinement study was developed in order to prove the aerodynamic results to be independent of the mesh size. The region of the boundary layer was discretised with a structured mesh to better represent the flow properties. It was also necessary to avoid a large cell size difference between the inflated layers and the first unstructured elements around the body to retain sufficient accuracy. Finally, a mesh refinement in the vorticity region was applied to better capture the tip and root vortices.

Due to its robustness and low computational cost, k-epsilon turbulence model, was chosen over the SST k-omega, as in upwind condition only small angles of attack were investigated and stall was not reached. The non-dimensionalised wall distance (y^+) was set to be in the logarithmic region, so that fully turbulent flow was expected in the boundary layer, [24].

Due to the height of the mast, the wind shear profile, described by the log-layer law was added to the simulations, taking as reference height the weather stations of the AC45 committee boats, [25, 26].

The aerodynamic forces are a function of wind speed, direction, sheeting and heel angles. Dependency on the latter was assessed and it was found that the following may be used to reduce the number of interpolation parameters: and to define lift and drag as function of heel. From the simulations the forces, moments, centres of effort, the lift and drag components were obtained. By analysing the results it was possible to identify a decrease in drag with increasing flow speed and a maximum lift coefficient occurring at a true wind speed of = 14 knots. Also, base drag of was estimated. Furthermore, a reduction of both lift and drag was found with increasing main sheeting angle " ". Applying twist to the wing resulted in a relatively small increase in lift coefficient and a consistent increase in drag. The latter values may be due to the high induced drag occurring at the gaps between rear wing elements. The centre of effort was found to be approximately at mid-span and was shown to reduce with increasing heel. Little variation in the centre of effort height due to twist was observed.

As discussed in [27], the forward foil suppresses the peak pressure at the leading edge of the downstream foil (see Figure 4). This phenomenon, known as slot effect, permits the aft aerofoil to have a boundary layer with decelerated flux speed coming from the lee-side of the forward aerofoil rather than at the true angle of attack. Furthermore, the presence of the aft aerofoil creates a strong upwash in the streamlines of the forward foil; therefore increasing the net lift of the system. Figure 5 shows the streamlines with the tip and root vortices visible.

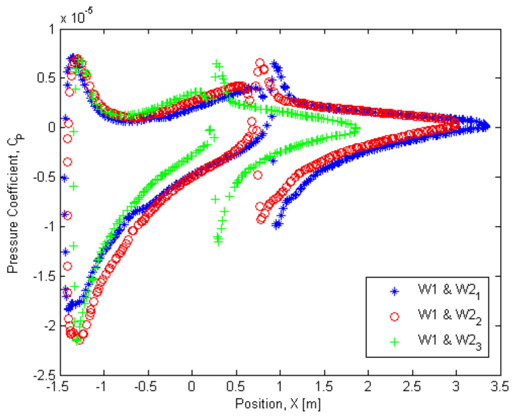

Figure 4: Pressure distribution along main wing and flaps: V T = 10 knots, TWA = 47 , and . The pressure distribution is shown at three different heights along the wing, namely at polylines evaluated at mid-span of each rear flap, top "1", midlle "2" and bottom "3" positions respectively. The effects of both front and rear wings is shown.

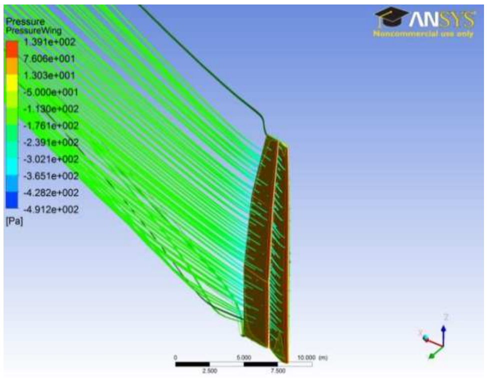

Figure 5: Streamline distribution in the domain: and TWA=47

2.4 GRAPHICS ENGINE

A detailed graphical model of the boat was created using the Rhinoceros 4.0 package. The boat was then exported and used with the VRML program integrated into the Simulink® package (see Figure 6).

To present a static frame of reference to the users, the buoys and laylines were placed in the race area so as to resemble an upwind leg of a race. Furthermore, a panoramic view of San Francisco was projected on a cylindrical boundary to give the users a sense of direction.

One of the main objectives in developing the graphics was to create a sense of motion of the boat that would allow the users to estimate the boat speed over water without them having to make use of the provided dials, much as it is done in real life. Also, emphasis was put on representing the wind direction in the form of graphical cues.

Figure 6: Screenshot from the simulator VRML environment showing the boat at the startline on a starboard tack. Note that the jib model was removed from the VRML visualisation due to lack of an appropriate modelling method.

Two possible view configurations were incorporated in the graphical display: first with the camera located behind the boat and providing an overview of the entire catamaran and second with the viewport located on the windward demihull at the position where the helm would sit in the actual boat (the viewport changes automatically after each tack). This setup allowed the degree of realism of the simulation to be more closely assessed and discussed with the participants.

2.5 VALIDATION

Figure 7 shows the velocity plots over a tack compared with the data available from the AC45 GPS position tracking system [1]. Two clear differences can be seen: an overestimation of the maximum boat velocity by approx. 20% and too slow turning rate resulting in an extended tack time.

There are two principle reasons for this. Firstly, the ratio of the drive-to-lift forces is approximately 35% larger than expected from the steady-state boat speed. This might originate from the hydrodynamic drag being underestimated by the less-than-ideal for this purpose NPL series, windage drag not being accounted for sufficiently well or the CFD analysis over predicting the aerodynamic drive force. Secondly, the rotary inertia in yaw (and partially in roll) is likely over estimated, hence leading to slower turning rates. Given the extremely light displacement of an AC45 boat even small discrepancies in this area will have a significant impact on the result obtained.

Speed loss experienced through the tack was significant, however not as great as in the case of actual AC45 catamarans. This might indicate that the hydrodynamic resistance under estimation is a primary defect of the physics model. Also, substantial simplifications of the unsteady effects surely played an important role in this behaviour. Nonetheless, the overall physics and relative trends in the boat behaviour resembled reality quite closely.

In an attempt to estimate the error magnitudes quoted above the inertias and net drive force were scaled by an arbitrary factor and the simulation runs were repeated with the recorded rudder and main sheet settings, yielding boat velocity also shown in Figure 7. It can be seen that a much closer convergence could be achieved by relatively small manipulations. The original setup was used in the human testing phase out of the fear that any arbitrary changes might influence the results to a greater extent than using the unmodified but less accurate version of the simulator.

3 TESTING

3.1 METHODOLOGY

In order to test the simulator two groups of participants were evaluated: beginners (little to no sailing knowledge) and experts (over 10 years of sailing experience with at least part of it on catamaran boats). Both groups were formed of ten participants. Prior to the actual tests the participants were given a few acclimatisation runs to understand how the simulator works and each team member's responsibilities. Subsequently, the teams had to complete 5 runs of 5 tacks each in to travel as much upwind as possible. This was aimed to represent an upwind leg of a race. It was considered that from the crew training point of view this would be more quantitative than examining the speed loss through the tack as it formed a clearer objective for the participants. Records were held of the simulation parameters and all contestants were asked to fill in questionnaires regarding their experience. In order to correctly model an upwind leg of a race, a number of wind speeds and directions were chosen as characteristic values in upwind courses using the AC45 GPS data.

3.2 DISCUSSION OF THE RESULTS

Almost all participants agreed that the physical interface was very ergonomic and comfortable as well as realistic. Frequently repeated comments appreciated the fitting of the toe straps, overall simulator layout and the use of the rudder and main sheet actuators. The key result obtained from the participant survey was that nearly everyone felt that they had improved their sailing and tactical skills over the simulated runs they took part in. Likewise, close to all participants thought that with a few improvements the simulator could be an essential and powerful training tool.

A significant proportion of the users felt that the graphics used did not resemble the real world closely enough. Typical comments pointed out its limited ability to create an impression of the boat motion and lack of a sufficient amount of cues regarding the heading of the boat with respect to the wind direction. Moreover, it has been frequently said by the users that incorporating a moving platform instead of the stationary set of benches and frames would add greatly to the simulator. Also, the use of hardware push buttons over the touch screen monitor was suggested to have a possible effect on the realism of the simulation and handling of the virtual boat. Certain members of the expert group thought that presenting a velocity polar diagram would allow them to trim the boat to its full potential. A single but very important comment suggested that use of a realistic set of sound effects would benefit the simulation realism greatly.

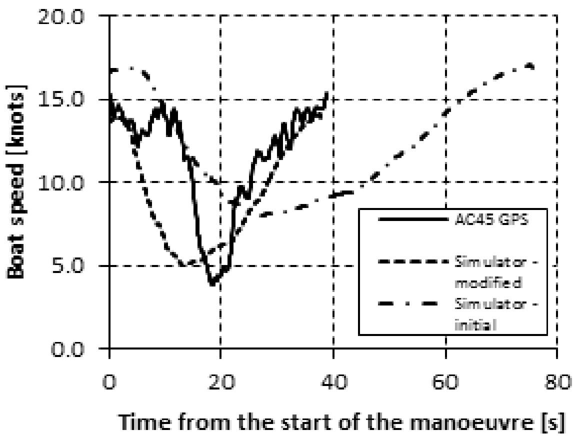

Figure7: Plot of the boat speed obtained from the AC45 GPS data, initial simulation runs and tests with the corrected inertia matrix and drive force magnitude.

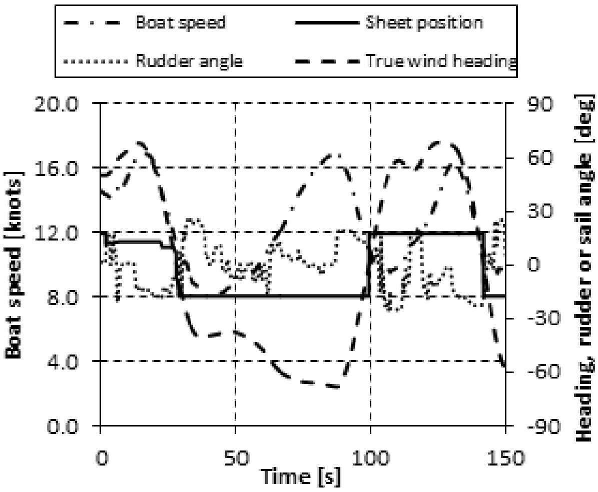

Figure 8: An example of boat parameters for a series of tacks carried out using the simulator.

In Figure 9 the mean speed of the boat and the standard deviation of the main sheet position can be seen for the two groups as a function of the number of test runs each team has accomplished. There is a clear difference between the average speed achieved by the novice and experienced sailors which indicates that there is an inherent level of realism in the simulation that causes the two groups to perform in a distinguishably different way. The speed achieved by the experts does not change significantly. However, there is a noticeable improvement in the velocity achieved by the novices. For the beginners the deviation in sheet position changed a lot more during the training session than it did for the experts. This suggests that the latter group have executed a much steadier control over the boat from the very beginning whereas the developed their skills by practice and experimentation.

In all of the results it can be observed that the novice group's performance improved much more significantly whereas the experts' scores were more stable but superior. This indicates that the simulator has the capability to teach and improve the users' sailing skills.

During the test sessions it could be clearly seen that the experienced sailors cooperated much more effectively than the novices. The latter group would often get confused and lose focus of the objective. While not necessarily clearly seen in the data, this very well resembled what can be observed on real boats in stressful situations. This indicated that the simulator has the potential not only to develop purely sailing skills, per se, but also improve the crew team work in much the same way as a practice session on the water would.

Errors in the analysis might have arisen due to multiple reasons. There could have been issues associated with the accuracy of the physics model and input/output processing of the actuators. Despite clear instructions certain teams adopted a different techniques of sailing around the course and so some of the results had to be disregarded from the analysis due to being significantly different (for instance in the case of a team who kept bearing away to a broad reach after each tack). Moreover, the testing was conducted over a period of two weeks and most of the test subjects were students from the same department and it is possible that there was an exchange of information on how to achieve best results in the simulation which could not have been prevented.

4 FUTURE WORK

Based on the success of the current simulator it is planned to continue with further research and development in order to improve it. This will principally revolve around enhancing the physics model, probably by implementing more refined force estimation methods. An interesting research topic which has emerged is the development of a 6 degree of freedom manoeuvring model for a sailing catamaran which would allow a broad range of phenomena to be computationally studied.

From the questionnaires it was concluded that the simulator might benefit from further development of the interface hardware so that it resembles the actual boat layout more closely. An example of this might be the addition of more realistic controls for the jib.

Modern video games technology allows excellent graphics to be introduced and this will certainly see increased interest in further development stages to enhance the representation of the boat and the entire sailing environment.

The budget allowed only a stationary physical interface design to be built. A substantially larger budget would have been required in order to build a physical interface capable of simulating motion in multiple degrees of freedom. Introducing this significant additional cost would also make it difficult for the Youth America's Cup teams and other interested sailing groups to access it. While a movable main platform would introduce an entire new level of realism and respond to the users' feedback, it has been shown that good training results can be achieved with just a static one. For these reasons such a configuration is worth considering in the future but the current setup should not be discarded completely.

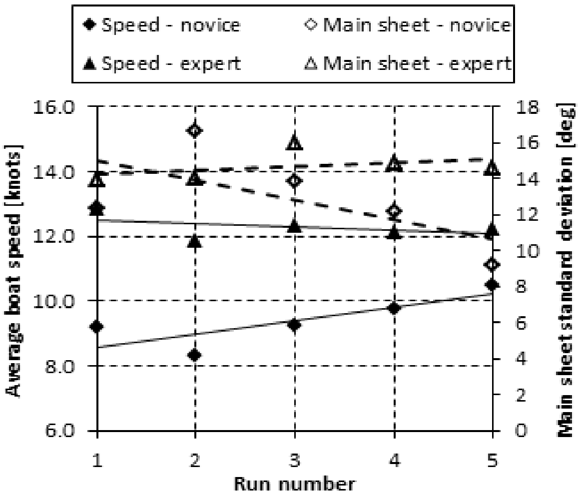

Figure 9: Standard deviation in the wing sail sheeting angle versus the number of runs (linear fit presented for each series).

5 CONCLUSIONS

The comparison of the boat speed variations obtained from the simulations with those provided by the America's Cup web site, as well as the comments and performance data gathered from the human testing of the simulator, have provided a solid basis for the future improvement and development of a virtual sailing environment to be used for the crew training purposes.

It has been verified and demonstrated that even given limited means and time a successful sailing simulator can be created and used to develop the skills of the crew. The most important conclusion regarding this aspect is that a suitable balance has to be achieved between focusing on the accuracy of the simulation, be it the fidelity of the force model or the race environment, and ensuring suitable level of realistic experience. It has been stated multiple times by the participants that they paid much attention to issues such as details of graphics, minor features of the physical interface and less so to the actual boat physics.

Based on the above it can be concluded that although a substantial amount of further investigation, research and development would be required in order to create a fully functional simulator that would suit the needs of training future America's Cup teams. Despite this fact at this stage it appears to be a perfectly feasible and potentially very beneficial solution.

Figure 10: The final setup of the simulator with a participants crew executing a tack manoeuvre.

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