APPLICATION OF SIMULATION TECHNOLOGY TO THE PERFORMANCE EVALUATION OF HMS VICTORY AS AN EXEMPLAR OF THE SHIPS WITHIN THE FLEETS AT THE BATTLE OF TRAFALGAR

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Summary

The production of a computer-based simulation representing an early 19th Century sailing warship is described. HMS Victory is used as a basis ship throughout the work. A broad overview is presented of the goals of the project. The particulars of HMS Victory are given and basic hydrostatic data calculated. The design and construction of both a 1:40 towing tank and wind tunnel scale models are described. The experimental procedures used during both sets of tests are detailed, along with the subsequent data analysis. Sample results are presented and regression functions fitted for use within the simulation. The software design decisions are outlined before the overview of Virtual Trafalgar's software architecture is presented. The implementation of the ship manoeuvring theory in the simulation physics engine is described and results from initial evaluations given.

Introduction

There is a high level of interest both generally and academically in the field of historical naval warfare, and specifically around the era of the Napoleonic wars. A wealth of information exists on the form of the ships used, the nuances of the rig, and the skills of seamanship. However there exists little technical data on the manoeuvring and sailing characteristics of these vessels. Logbooks and anecdotal evidence provide a qualitative flavour of the performance of the large wooden sailing ship, but little is known in quantitative terms of their performance.

It was decided to develop a computer based simulator that would, as accurately as possible, model the performance of a ship at the battle of Trafalgar. By combining modern techniques for the assessment of the manoeuvring and sailing performance of ships such a simulator is possible. It requires the use of appropriate scale model testing as well as theoretical analysis to generate sufficient veracity in performance prediction. The fighting ships of the late 18th and early 19th century where of similar form and so detailed study of one specific ship should allow the performance of the others to be derived. The relative wealth of information and the fact that HMS Victory is still in commission, albeit in drydock, meant she was the obvious choice.

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This paper will concentrate on the experimental testing and development of the numerical simulation and give an overview of all aspects of the work carried out to date. Fuller information can be obtained from [1].

Approach to Problem

Any ship, conventionally powered or wind driven, responds to the marine environment; the wind, wave and ocean currents according to its physical shape, mass distribution, underwater hydrodynamic characteristics of the hull and the aerodynamic characteristics of the superstructure and sail/rigging arrangements if present. At its most basic level the response of the ship can be stated in terms of a balance of forces and moments. These consist of six individual equations that are conventionally expressed as:

(i) Translational motion along three axes. An excess of force, X, along say the ship x axis perhaps caused by a wind gust will cause the ship to accelerate (surge, u) forward. Differences in sideforce, Y, or vertical force cause sway, v, and heave motions.

(ii) Rotational motion about the same three axes are referred to as roll, pitch and yaw, ψ.

In order to simulate the manoeuvring and performance of a ship, such as HMS *Victory*, in the time domain it is necessary that at any instant that all the individual components of forces and moments are known. If these are known then the speed and direction of the ship can be predicted at some sufficiently small time step in the future. Repeating this process for an arbitrary period time will allow the manoeuvring behaviour of the ship to be fully described or indeed for multiple ships that of a complete fleet or fleets. What is important for a realistic simulation is that necessary changes in the marine environment (wind, waves, current) and in the ship (helm angle, number and types of sails and their individual settings, mass and its distribution) also need to vary with time in a realistic manner.

Within the software the physics engine implements the method used by the computer to move an object through the virtual world. If the program is one where there are objects moving in real time the physics engine must be able to update the position for each object for each refresh of the screen. The ideal physics engine would provide an analytical solution to the equations of motion. In a situation where all of the hydrodynamic and aerodynamic forces acting on a ship have to be evaluated. The complexity of the equations and their associated variables makes it necessary to employ a numerical method.

When considering the motion of a real ship there exist six degrees of freedom. However, it is a reasonable approximation for manoeuvring to only examine the ship's longitudinal and lateral force balance and the moments about the vertical axis. that is surge, u, sway, v, and yaw, ψ [2]. Three degrees of freedom yield three equations of motion which can be expressed in the ship's rotating frame of reference as

$$
\begin{aligned}
X &= m\left(\dot{u} - v\dot{\psi}\right) \\
Y &= m\left(\dot{v} + u\dot{\psi}\right) , \\
N &= I_Z \ddot{\psi}
\end{aligned}
$$

where m is the ship's mass, I_z its rotational moment of inertia and N the moment about the vertical axis.

The hydrodynamic forces on a ship's hull can be considered as functions of the linear and angular velocities and accelerations. Hence:

$$
\begin{aligned}
X &= f\left(u, \dot{u}, v, \dot{v}, \psi, \dot{\psi}\right) \\
Y &= f\left(u, \dot{u}, v, \dot{v}, \psi, \dot{\psi}\right) . \\
N &= f\left(u, \dot{u}, v, \dot{v}, \psi, \dot{\psi}\right)
\end{aligned}
$$

These in turn can be approximated using a Taylor expansion.

$$
f\left(x\right) = f\left(x_1\right) + \Delta u \frac{df(x_1)}{du} + \Delta \dot{u} \frac{df(x_1)}{d\dot{u}} + \Delta v \frac{df(x_1)}{dv} + \ldots + \frac{\Delta u^2}{2!} \frac{d^2 f(x_1)}{du^2} + \ldots ,
$$

where $x = f(u, \dot{u}, v, \dot{v}, \psi, \dot{\psi})$ and x_1 refers to an equilibrium condition. If such Taylor expansions are truncated to just the first order derivatives, all the forces/moments can be expressed in terms of manoeuvring derivatives that can either be experimentally measured or theoretically calculated.

A non-linear function that represents the ship's longitudinal resistance D is given by:

$$
D = \tfrac{1}{2} \rho u^2 S_{wet} C_T\left(Fn, Rn\right) \text{ where } Fn = \frac{u}{\sqrt{gL}} \text{ and } Rn = \frac{\rho u L}{\mu} ,
$$

where C_T is based upon the Froude, Fn, and Reynolds, Rn, numbers, and can be a mathematical function or obtained computationally from a lookup table.

The total forces can be found from

$$
\begin{aligned}
f_X &= D\left(u, Rn, Fn\right) + mvr + X_\delta \delta + H_X \\
f_Y &= Y_v v + Y_r r - mur + Y_\delta \delta + H_Y \quad , \\
f_N &= N_v v + N_r r + N_\delta \delta + H_N
\end{aligned}
$$

where the $\boldsymbol{H}$ components represent the force/moment contributions of the sail rig, δ is the rudder angle and the subscript indicates a derivative with respect to that quantity evaluated at the equilibrium condition (note the yaw rate $r = \dot{\psi}$ and $\dot{r} = \ddot{\psi}$). The instantaneous acceleration can then be found by

$$\begin{pmatrix}\dot{u}\\ \dot{v}\\ \dot{r}\end{pmatrix}=\begin{bmatrix}\frac{1}{m-X_{\dot{u}}} & 0 & 0\\ 0 & \frac{(I_Z-N_{\dot{r}})}{(m-Y_{\dot{v}})(I_Z-N_{\dot{r}})-Y_{\dot{r}}N_{\dot{v}}} & \frac{Y_{\dot{r}}}{(m-Y_{\dot{v}})(I_Z-N_{\dot{r}})-Y_{\dot{r}}N_{\dot{v}}}\\ 0 & \frac{N_{\dot{v}}}{(m-Y_{\dot{v}})(I_Z-N_{\dot{r}})-Y_{\dot{r}}N_{\dot{v}}} & \frac{(m-Y_{\dot{v}})}{(m-Y_{\dot{v}})(I_Z-N_{\dot{r}})-Y_{\dot{r}}N_{\dot{v}}}\end{bmatrix}\begin{pmatrix}f_X\\ f_Y\\ f_N\end{pmatrix}.$$

As long as all the manoeuvring derivatives are known then a standard Euler, or more accurate Runge-Kutta time advancing scheme, can be used to move to the next time step; where the process of evaluating forces and recalculating accelerations is repeated. The following sections describe the process of evaluating all the necessary forces and manoeuvring derivatives.

Particulars of *HMS Victory*

The particulars of *HMS Victory* are given[3] as is the body plan, see Figure 1. The overall length between perpendiculars, L_{BP}, is 56.9 m,with a breadth of 15.4 m and draught of 6.95m.

A first step in the modelling of a ship is to calculate the volume of the geometric form to a given waterline. The ship lines software package ShipShape was used to do this. A `network' is created consisting of transverse sections and connecting longitudinal splines. The transverse sections were taken from the offsets measured from the available body plan whilst the longitudinals that linked these sections from waterlines. By representing the ship form in this way flexibility is provided to recalculate these parameters as necessary, for instance at different waterlines corresponding to different load conditions. These particulars, as calculated for the fully loaded condition, are shown in Table 1.

Table 1 Hydrostatics at Load Waterline for *HMS Victory*

Draught	6.95 m
MCT	27.234 tonne-m/cm
LCB	-0.92m
LCF	-0.24m
VCB	4.08 m

Mass Distribution

An understanding of the longitudinal weight distribution of the ship is necessary for the creation of the simulation. The moment of inertia of the ship about its longitudinal centre of gravity, LCG, position, I_z, describes the necessary moment to cause a specific change in the rotation of the vessel.

On a vessel of any size it is not possible to entirely model the distribution of weight, and this is especially true for a ship as large and complex as *HMS Victory*. Therefore a number of simplifying assumptions have been made.

The weight of the hull itself was estimated using an empirical formula provided in [4].

$$W_H = \frac{LB + BD + LD}{a} + b$$

where W_H is the weight of the unrigged lightship hull. Constants a and b depend upon ship type. For a 3-decker such as *HMS Victory*: $a=8.7$ and $b=446$. However, [4] notes that the sample for 3 deckers is insufficient and so this equation should be treated with caution. Using these constants the weight of the hull is calculated as 648 tonnes.

It is also necessary for the calculation of I_z to model the distribution of the weight along the hull. For this a 'coffin' diagram distribution was used. The general form of this distribution is shown in Fig. 2. The weight of the hull is equal to the total area under the graph. The chosen length of the parallel midbody of the ship, L_{pp}, is actually longer than the strictly defined midship section of same cross section; this extends over only about 20 m in the centre of the ship, whilst the value of L_p used is 30.93 m. However, it was considered that a larger value gave a more accurate representation of the ship's shape.

The constant d is chosen based on the value of L_p/L. A value of 1.15, as used here, is considered suitable based on accepted practice for merchant ships. The values of a and b are chosen so as to ensure the centroid of the area of the diagram is consistent with the LCG of the ship. The LCG used for this purpose was taken to equal the LCB as calculated in the hydrostatics program, a situation satisfied in level trim. A summary of the calculations is given in Table 2.

Table 2 Coffin diagram components

Component	Area (mass/tonnes)	Aft Extent (m)	Fwd Extent (m)	Centroid position	Centroid * Area
aft rectangle	273.5684191	-28.19	-12.83	-20.51	-5610.888275
aft triangle	78.69776439	-28.19	-12.83	-17.95	-1412.624871
Parallel midbody	867.819981	-12.83	18.11	2.64	2291.04475
forward rectangle	34.43027192	18.11	28.19	23.15	797.060795
forward triangle	124.1949094	18.11	28.19	21.47	2666.464706
total	1378.711346			HULL LCG	-0.920383298

A significant proportion of the weight of the ship consists of the armament. The guns onboard *HMS Victory* at the time of the battle of Trafalgar and their associated weights are summarised in Table 3.

Table 3 Guns And Their Weights And Distribution

	Position	Number	Weight (tonnes)	Total Weight (tonnes)
32 pounder	Lower Gun Deck	30	3.276	98.28
24 pounder	Middle Gun Deck	28	2.923	81.844
12 pounder	Upper Gun Deck	30	2.021	60.63
12 pounder	Quarter Deck	12	1.905	22.86
12 pounder	Forecaslte	2	1.845	3.69
TOTAL		102		267.304

These are disproportionately influential on the calculation of I_z because they are evenly distributed in weight along the hull. This is as opposed to other weights, such as the hull and stores, which tend to be concentrated more towards the centre of the vessel. The contribution to I_z of all the guns on each deck was modelled as a rectangular box. The longitudinal extent of the guns on each deck where scaled from a 1/192 general arrangement [5].

The stores carried by HMS Victory when fully provisioned [5] are summarised in Table 4. This Table also shows the position of the 'accounted' stores in the ship's hull. These were stores in locations identifiable on the general arrangement already mentioned. The remaining stores were presumed to be in the hold, the extents of which were also taken from the general arrangement drawing.

Table 4 Stores Carried And Their Weights And Location

	Description	Weight (tones)	Longitudinal aft extent position from midships (m)	Longitudinal forward extent position from midships (m)
'Accounted' Stores	Biscuits	45	-27.264	-21.312
	Flour	10	-19.392	-15.744
	Shot	120	-5.568	-4.8
	Beer	50	12.864	13.824
	Powder	35	15.744	21.504
	TOTAL	260		
Other Stores	Water	300		
	Fuel	50		
	Butter	2		
	Saltmeat	30	-12.48	11.712
	Pease	15		
	Timber	20		
	TOTAL	417		

In a similar manner to the guns, each subset of stores was modelled as a rectangular box along the hull length.

HMS Victory carried approximately 1148 tonnes of ballast as a mixture of iron and shingle in her hold. The ballast has been modelled using the same technique as above along the length of the hold. She also carried a total of approximately 32 tonnes of various anchors. Two of the heaviest anchors, totalling 15.24 tonnes, have been modelled far forward where they would have been stored, whilst the rest have been regarded as spares and placed in the hold.

The total of all the weights calculated above leaves a deficit of approximately 730 tonnes of weight not accounted for. A significant contribution to this is probably the masts and rigging, but other weights such as crew and their provisions and smaller items of outfit have also not been included. It was decided that the most appropriate way to include this weight in the final calculation of I_z was to add it to the hull weight that has been distributed using the coffin diagram along the ship length. It could be argued that this weight would be best modelled concentrated at the positions of the masts and along the bow sprit. However a consideration of even the thickest point of the masts gives a weight of less than a ton per metre length, which gives a total weight of the masts that is significantly less than the weight excess. It is therefore considered more accurate to consider this remaining weight as being distributed in a similar fashion to the hull weight.

Table 5 compares the calculated value of I_z to three benchmarks; a rectangular box of similar dimensions, the Mariner hull form and an America's Cup yacht[6].

Table 5 Comparison of Iz for a Range Of Hull Forms

	HMS *Victory*	Rectangular box of $L \times B$	Full size *Mariner* hull	America's Cup Yacht
I_z	2.7447E+08	9.9719E+08	8.61E+09	2.03E+05

The weight of the modelled *HMS Victory* is more central than that for a solid rectangular box of similar dimensions, and so it is encouraging that the I_z for such a rectangular box is larger but of the same magnitude. Equally the Mariner form is physically larger and so a higher value of I_z is to be expected, whilst the much smaller and lighter America's Cup Yacht has a much smaller I_z. From these comparisons, the derived estimate of I_z is considered reasonable.

Vertical Weight Distribution

The height of the vertical centre of gravity, VCG, is necessary in order that the righting moment on the ship in roll can be modelled. Although this is not included for the manoeuvring simulation it is required for an accurate visual representation of the ship roll motions. The calculation of VCG is not realistic, given the complexity of the vessel and rig. Instead, the standard method of finding the VCG of a ship is through the performance of an inclining experiment. Such an experiment was performed whilst the ship was still afloat in 1921[7]. The calculated displacement at the time of this experiment was *3174* tonnes. In this condition, GM_T, was calculated as *1.771* m. Since KM_T is a function of the shape of the underwater hull that can easily be calculated by the ShipShape program, it is thus possible to find the position of the VCG. Using this method the VCG of the ship is calculated at 6.601 m at the tested displacement of 3174 tonnes. To include the weight to increase the displacement of the ship to load displacement, the extra weight is modelled as a moment acting 2 m above the keel, likely, given that the majority of the extra weight was probably stores not included when the ship was provisioned for port duties as it would have been in 1921. This gives a load VCG of 6.17m.

GZ curve

In order to model a ship's response to roll it is normal to investigate the variation in the length of the righting lever GZ over a range of heel angles. Whilst in traditional ship design this is performed in order that a level of regulatory stability is achieved, here it is required for the calculation of the roll restoring moment. Figure 3 shows the GZ curve created by exporting the ShipShape hull model into the Wolfson Unit hydrostatics program.

Hydrodynamic tests

In order for the data collected in the series of towing tank tests to be applied to the simulation, trends must be identified that can be delivered in a useful format to the software. Broadly, the information required from the towing tank data breaks down into two areas. Firstly, the analysis of drag and side forces generated in the various conditions tested. Secondly, the collection of the slow motion manoeuvring coefficients required to model the response of the ship to externally applied forces, sails and rudder actions. Where necessary information for the simulation could not be extracted from the experimental results, it has been calculated by other means.

The towing tank used is the Lamont Tank at the University of Southampton. The tank is 30 m long, of 2.4 m breadth and 1.2 m depth [8]. The model is towed by an unmanned carriage with a maximum speed of 2.5 m/s. An automated system measures the time taken by the model to travel a 10 m central section over which the carriage speed is constant. The standard towpost dynamometry measures drag force, side force and heel force as required. The maximum viable model size was chosen to be $1/40^{th}$.

Model manufacture

Scaling the ship displacement gives a model displacement of *52.43* kg in fresh water. As the model is to be manufactured from a block of solid modelling foam the volume of the hull (and hence the weight of the foam) are critical. To keep the weight of the model down for the towing tank tests the towing model is only modelled as far as the mid gun deck.

The model was machined from two solid blocks of modelling foam using a CNC milling machine, Fig. 4. The blocks were mirror images of each other, consisting of the port and starboard sides of the vessel. The offsets were generated from the ShipShape model. The keel piece was manufactured separately from a laminate of two pieces of 6 mm plywood. The model was fitted with a rudder that could be set at various marked angles. Standard trip studs were applied.

Test Conducted

In order to derive all the necessary data for the simulation the test matrix was required to investigate changes in speed, angles of leeway, angles of heel, applied rudder angle and displacement. The utilised test matrix is outlined in Table 7.

Table 7 Test matrix where motor rpm controls carriage speed

Speed (Motor RPM)	Heel Angle (deg.)	Leeway Angle (deg.)	Rudder Angle (deg.)	Displacement (kg)
150, 200, 250, 300, 350	-15, -10, -5, 0, 5, 10, 15	0	0	55, 60, 65
250	0	0	-45, -30, -15, 0, 15, 30, 45	55
250	-10	5, 10, 15		55
250	10	-5, -10, -15		55

As a sailing ship it would have been normal for *HMS Victory* to be moving at forward speed with an angle of heel. However, this angle would not have been very large due to the early onset of down flooding through the gun ports, which were not watertight. It was calculated that the maximum angle of heel would not be greater than about 10 degrees when at load displacement.

Results and analysis

For a hull form such as that of HMS *Victory* the bare hull resistance will be dominated by frictional resistance, C_F. The residuary resistance, C_R, will be a small component and is found using frictional resistance estimated using the IttC 1957 friction line and subtracted from the non-dimensional total measured resistance force, C_T.

$$C_R = C_T - C_F \quad \text{where } C_{R,T,F} = \frac{R_R, R_T, R_F}{\frac{1}{2}\rho U^2 S} \text{ and } C_F = \frac{0.075}{\ln(Rn-2)^2}$$

ρ is the water density, U the ship speed and S the hull wetted surface area and the appropriate Reynolds number is given by $Rn = \rho UL/\mu$. At the lower speeds tested, experimental; scatter can be seen as shown in Fig. 5 for the upright, loaded displacement condition. A fitted polynomial curve was found to represent the behaviour of the hull resistance. As part of the simulation the resistance at full scale is found by first calculating C_F. Similar behaviour was found for the differing load conditions.

Induced Lift and Drag at Angles of Leeway

For the loaded condition a range of leeway angles were tested at a *Fn* of 0.17. An increase in C_R was seen over this range, and was found to be linearly proportional to the square of the leeway angle as shown in Fig. 6. In this figure it is the ratio of the value of C_R to the 0^o leeway condition value of C_R that is plotted against leeway angle squared. If the induced drag that causes the increase in C_R with leeway angle is considered largely *Rn* independent, then the ratios may be applied to other speeds given an initial 0^o leeway angle value of C_R taken from the upright resistance curve. Thus, the experimental data may be used to find the increase in C_R for a given leeway angle over a range of speeds.

In a similar fashion, it is desirable to be able to relate increases in the ratio C_R/C_{R_0} to the side, or `lift' force produced. Thus Fig. 7 shows the relation between this ratio and the square of the non dimensional lift coefficient, C_L. This is resolved perpendicular to the axis of the tank consistent with the resolution of C_R mentioned above. Once again, if lift force is assumed *Rn* independent, then the increase in C_L can be related to the increase in C_R, and hence the side force for a given speed and leeway condition may be estimated.

For the tests which investigated the influence of leeway and rudder angle the model was attached to the tow post using fore and aft dynamometers. This allowed the position of the centre of lateral resistance (CLR) to be found. The influence of the square of leeway angles (in radians) is shown in Fig. 8.

Estimation of Manoeuvring Derivatives

It was not possible to measure all the manoeuvring derivatives required by the equations of motion. However, using tests conducted over varying angles of leeway and rudder angles, it has been possible to experimentally calculate the derivatives Y_v and N_v and the effects of the rudder on these and all the other derivatives. These will then be combined with semi-empirically derived derivatives to provide an estimate in the simulation of the manoeuvring characteristics of *HMS Victory*.

These coefficients are determined from a study of the relationship between the side force produced and the sway velocity. The values of these coefficient are best obtained from the analysis of a graphical plot of ΔY compared to v and ΔN compared to v respectively.

$$\Delta Y = -531.61v^3 + 17.273v^2 - 41.363v + 0.2234$$
$$\Delta N = 154.68v^3 - 2.7076v^2 - 18.921v + 0.1188 \, .$$

These derivatives are specific to the scale of the ship. Manoeuvring derivatives for surface ships may be considered independent of *Rn*. The non dimensional forms of these derivatives Y'_v and N'_v are expressed as:

$$Y_v' = \frac{Y_v}{\frac{1}{2}\rho U L^2} = -63.87x10^{-3}$$
$$N_v' = \frac{N_v}{\frac{1}{2}\rho U L^3} = -20.2605x10^{-3} \, .$$

The actions of the rudder are modelled in the equations of motion in two ways. Firstly, the non dimensional rudder derivatives Y'_ζ and N'_ζ exist as separate additions on the force side of the equations of motion. Secondly the existing velocity derivatives Y'_r, N'_r, Y'_v and N'_v are modified by the existence of the rudder at an angle of incidence. The alteration to these derivatives under the action of the rudder is performed linearly. The evaluation of these derivatives requires the measurement of the influence of rudder angle on sideforce for a range of leeway angles. Figure 9 shows the plot of sideforce for a Fn = 0.17 and a linear trend is shown. Table 8 compares the values of $dC_L/d\alpha$ where $C_L = Y / \frac{1}{2}\rho U^2 L^2$ and α is in radians , for the range of leeways tested.

Table 8 Variation in $\partial C_L / \partial C_\alpha$ Over a Range of Leeway Angles

Leeway Angle	a (at model scale)	$\partial C_L/\partial\alpha$
0	-0.59	9.4935
5	-0.59	9.5742
-5	-0.59	10.115
-10	-0.59	12.128
10	-0.59	12.133
15	-0.59	15.339

The corresponding variation in $\partial C_L / \partial C_\alpha$ compared to the leeway angle squared is shown in Fig. 10. The trend line shown is used in the simulation to model the measured change in the effectiveness of the rudder at various angles of leeway.

As it was not possible to obtain all the required manoeuvring derivatives experimentally, it was necessary to find alternative means to determine their value. Such an approach has been developed [9] and considers the semi-empirical derivation of manoeuvring derivatives for single screw merchant ship forms based on the basic hull dimensions of *L, B, T* and associated derived ratios as well as C_B. The variation in these derivatives makes the drawing of such trends difficult, and their use for a hull form that varies from those studied as much as *HMS Victory* is questionable. However, it was felt that this was the best way to create some initial derivatives for use in the simulation.

The total set of manoeuvring derivatives for HMS Victor as calculated from the semi-empirical formulae is shown in Table 9. Two of these estimated derivatives, Y'_v and N'_v, are compared to their experimentally calculated values. All the non-dimensional derivatives are compared to those of the merchant hull form, the Mariner, and an IACC yacht. Each of these derivatives has been estimated using the semi-empirical formulae alongside their previously determined experimental values.

Table 9 Experimentally and Semi-Empirically Derived Derivatives for *HMS Victory*, a Mariner Hull and an America's Cup Yacht (Note manoeuvring derivatives *x10*^{3})

	HMS *Victory*		*Mariner*		America's Cup Yacht Canoe Body	
T/L	0.1221		0.0469		0.0435	
$\pi \times (T/L)^2$	0.0469		0.0069		0.0059	
B/L	0.2707		0.1440		0.2030	
B/T	2.2158		3.0720		4.6700	
C_B	0.5699		0.5978		0.3928	
Prediction Method	Semi-Empirical [12]	Experiment	Semi-Empirical [12]	Experiment [14]	Semi-Empirical [12]	Experiment [13]
Y_v		41.36				
N_v		18.66				
Y'_v	-70.54	-63.88	-11.97	-10	-10.30	-1.9
N'_v	-37.17	-20.26	-4.23	-3.5	-3.59	-6.1
Y'_r	3.84		2.96	3	2.54	2.8
N'_r	-8.66		-2.00	-2.5	-1.89	-0.8
$Y'_{\dot{v}}$	-38.83		-8.20	-7.25	-6.43	-4
$N'_{\dot{v}}$	-9.70		-0.22	-0.45	-0.19	-0.37
$Y'_{\dot{r}}$	-7.74		-0.45	0.33	-0.38	-0.66
$N'_{\dot{r}}$	-0.73		-0.46	-0.42	-0.28	1.3

The ratio, *T/L*, is the most significant variation in the geometry of *HMS Victory* from the other vessels considered. This has implications for the accuracy of the semi-empirical equations in the estimation of derivatives, as $\pi (T/L)^2$ is associated with the derivative in all the equations.

However it is felt that the use of these equations for the estimation of the derivatives remains valid. The experimental results confirm for two of the derivatives that a significantly larger order of magnitude for their value is plausible. The experimentally derived derivative values for both a canoe body and a keel sailing yacht [6] show that a keel is seen to increase the value of the derivatives. This is to be expected since a keel provides resistance to changes in sway and yaw motion. It is similarly expected that a relatively high *T/L* ratio would produce the same effect.

Aerodynamic Performance Tests

Rig Model Construction

A 1:40 scale model of the above water arrangement was manufactured. The standard procedure for sail rig testing uses a shallow trough of water mounted on a turntable [10]. The dynamometry for measuring forces and moments on the model is attached to it via two bars (one set into the stem of the model, the other running through the hull athwartships) clamped to three flexure points on the turntable.

A shell-on-frame method, with frames cut from 6 mm ply was used to manufacture the model. This required the production of the centreline profile piece and 28 transverse frames. The complex structures at the bow and stern were simplified as far as possible, but still posed some interesting problems in their design and manufacture. The stern of a sailing warship appears from a lines plan to be an extremely complex shape, curved in every plane. On close inspection it was realised that the stern lines actually described a series of circular arcs, each of which lay not in the horizontal plane but in one normal to the stern profile. Ply formers following these arcs were made up and let into the profile piece. The manufacture of the bow and stern structure progressed in parallel with that of the rest of the hull and can be seen in the construction photographs, Fig. 11. Hardwood dowel was used for all spars on the wind tunnel model. All the major spars were included, with each mast made from three sections as on the real ship. Yards were hung using hooks and eyes to allow free rotation and easy removal. All spars are close to scale diameter, but were left untapered.

Sails were produced based on the sail plans [3] from cotton fabric, with a boltrope sewn into the hem and a loop in this boltrope at each clew. On the upper square sails this loop engaged with a hook screwed into the yard below, on other sails the loop was used to attach running rigging. Where a sail had to fit on to a spar a sleeve was put in for the purpose. A single line sewn along the luff of each triangular sail substituted for both the stay and hallyard. The lower end of this line was tied through a hole in the bowsprit and the upper end tied or cleated on the foremast. While the rigging was to be simplified as far as possible much of it had to be included, both for aerodynamic accuracy and structural strength. Detailed information on the rigging of *HMS Victory* was obtained from [11].

A 4-channel remote control was fitted using sail servos. This enabled the driver boom sheet and the lower yard braces on each mast to be operated from the control room while the tunnel was running. Upper yards were simply pulled round to follow the lower yards by their respective sails. This was deemed adequate but was not ideal as the degree of twist in the sails could not be controlled. Rigging followed the same paths as on the full-size ship as closely as possible[11].

Model Testing

The slow-speed working section of the 7'x5' wind tunnel at the University of Southampton was used for the tests. This section measures 4.57 x 3.65 m with a top wind speed of around 11 m/s. For these tests a wind speed of 4 m/s used, although checks were carried out for speeds between 3 – 5m/s.

As the simulation will allow the user to change the sail configuration of the ship, the test matrix had to be designed so that the effect of each sail could be found. Testing each sail by itself and subtracting hull and rig windage ran the risk of forces being too small for the dynamometry to measure accurately, as well as completely ignoring potential interference effects between sails. A range of sail configurations was therefore tested and the effects of each sail found from the differences in the forces generated by each rig. The lift and drag force on each sail were then non-dimensionalised to a local C_L and C_D based on the area of the individual sail. Corrections for residual zero error and blockage effects were applied to the forces measured by the wind tunnel dynamometers [12]. A total of 362 sets of data were acquired, with 20 different sail configurations (including two sets of windage readings, with sails furled and unbent respectively). Tests were conducted for a full range of heading angles and for variations in brace angles using the 4 servos connected to the three main masts and the driver.

It was necessary to know the area of each sail used in the testing, both for non-dimensionalising force data and for calculating the blockage correction for each sail configuration. Since no detailed sail area data was available for *HMS Victory* the sail areas were calculated from direct measurements of the model sails. This also meant that the areas would be those of the sails actually used in the testing, so any small differences between the actual sails and the plans would be accommodated.

It was not practical to evaluate the interaction between every possible pair of sails. When designing the test matrix some attention was paid to standard sailing practice of the period, so that the data would relate to realistic configurations; for example, topgallants would be unlikely to be set without topsails. The main consideration when working out the test matrix, however, was ensuring that the effects of most sails could be found by subtracting only one set of forces from another. The longitudinal and vertical centre of effort for the sails was also found from the dynamometer readings.

Results and analysis

Polynomial regression lines were fitted to the plots of sideforce, C_L and drag C_D. for a particular sail. Example plots, with regression lines fitted, are given in Figs. 12 and 13. The data showed some variation in quality; the distributions for some sails showed obvious trends and produced good and realistic regression fits, for others the data was sparse and displayed so much scatter that it was difficult to identify trends.

However, there did seem to be a high degree of consistency across the C_L and C_D distributions for the square sails and the distributions matched the expected shape. The data for the topsails was the most comprehensive and appeared to be of the highest quality, so it was decided to use the regression functions for the main and mizzen topsails to model the behaviour of all the square sails. The regression line for the fore topsail was a rather different shape to the other two and, given their consistency with each other, was considered less reliable. It was noticed that optimum C_L for the mizzen occurred at a slightly higher incidence angle than the main; given this difference, the function for the mizzen topsail was used for the mizzen topsail and topgallant, while that for the main was used for all sails on the main and fore masts.

This approach may lead to unrealistically large effects from the courses in the simulation (Peak C_L for the main course appeared to be around 0.7, compared to corresponding values for the topsails of around 1.8--2.0), but there was too much scatter in the course data to fit a reliable function. Data for the fore course was also sparse and had only been obtained when the main was set. The apparently lower lift and drag on the courses could be partly due to wind gradient effects, which could be accounted for by the inclusion of a suitable wind gradient model in the software.

The data for the driver was quite comprehensive and yielded good regression fits, as did the data for hull windage. The data for the triangular headsails (the forestaysails, jib and flying jib) was not as good. Again there were not many data points and only the flying jib data showed an obvious trend. A regression function was fitted to this, then scaled (by a factor of 0.5) to fit the data for the other triangular sails.

The regression equations used in the simulation so far are as follows:

Windage
$$C_L = -0.1762\alpha^4 + 1.15\alpha^3 - 2.3662\alpha^2 + 1.541\alpha + 0.0145$$
$$C_D = -0.2429\alpha^4 + 1.530\alpha^3 - 2.8875\alpha^2 + 1.7616\alpha + 0.0179$$

Flying Jib
$$C_L = -2.794\alpha^2 + 7.5172\alpha - 3.0915$$
$$C_D = -2.1744\alpha^2 + 6.6501\alpha - 3.726$$

Driver
$$C_L = -0.4698\alpha^2 + 1.173\alpha - 0.1077$$
$$C_D = -0.6115\alpha^3 + 3.0175\alpha^2 - 3.5805\alpha + 1.4662$$

Main topsail
$$C_L = -2.5528\alpha^2 + 3.7977\alpha + 0.5674$$
$$C_D = -0.0141\alpha^3 - 0.7776\alpha^2 + 3.4205\alpha + 0.0793$$

Mizzen topsail
$$C_L = -2.745\alpha^2 + 5.3629\alpha - 0.6103$$
$$C_D = 1.5308\alpha^3 - 2.8875\alpha^2 + 1.7616\alpha - 0.8899$$

where α is in radians and is the effective angle of attack seen by the sail which takes into account the effect of wind speed, ship speed and bracing angle. These functions are only valid within the range of incidence angles covered by the available data, which never exceeded 180^o and was often less than this.

Virtual Reality Simulation

The Virtual Trafalgar simulation had a number of requirements.

- Vessels must move at the correct speed in the correct direction for the sail, wind and sea combination.
- Vessels must respond to commands in the correct manner, and in the correct amount of time.
- Vessels must roll, heave and sway in a realistic manner. The simulation must be entirely 3D, and preferably look as realistic as possible.
- The simulation must be configurable, ideally allowing anyone to change the performance of a ship without specialist software.

After a review of possible options it was decided to develop a simulator using an open source graphics software package[13], further information about the software development is given in[1]. To date, more than 5,000 lines of new code have been written to run alongside the open source graphics procedures. A significant fraction of these are associated with the visualisation of a realistic sea surface.

<u>3D Model of HMS Victory</u>

In addition to the physical realistic behaviour of the sailing ship itself a suitable 3D model was also needed within the simulator. This was created using the Blender package[14]. However, it was still a complicated and time consuming process to produce a model in Blender suitable for use with Ogre.

For accurate modelling of a vessel the body and lines plans in [3] were used. Once digitised, the body plan can be used as a background image in Blender. This allows the accurately position vertices along each of the marked stations. The lines plan can then be placed as the background image to add the correct longitudinal spacing between the different hull frames. With this simple process, the bulk of the modelling of the hull is complete. Adding masts to the model is accomplished by adding basic objects (i.e. cubes, cylinders) and extruding, deforming and editing them as required. In creating the 3D model of *HMS Victory* detailed images of the ship's hull from [5] were mapped onto the mesh of the hull to create a far more realistic result than could be achieved with simple textures, and without the need to model every surface feature of the ship in 3D with vertices, lines and surfaces, see Fig. 17.

<u>Overview of Software Architecture</u>

The Virtual Trafalgar simulation has been developed as a number of specific modules. These are shown in Fig. 15 along with the interactions between each module. Included in this architecture are a number of modules that have not yet been implemented. Data files based on XML schema provide a straightforward method of the ship performance (helm, sail settings, loading) and its environment (wind, waves, current).

The Fleet subsystem is intended to provide the main application access to the fleet as a whole, and to individual ships. It also acts as an interface between the individual ships and the rest of the application. It is responsible for maintaining a list of all the active ships, and to ensure every ship is properly updated each frame. The Fleet is also responsible for interactions between ships. For example, if collision detection were to be implemented, the fleet would be notified of the collision, and would then be responsible for notifying each ship of the collision.

The Ship Plugins encapsulates all the functionality of a single ship. It is responsible for moving the ship in the correct manner in response to messages from the Fleet and the user via the graphical user interface, GUI.

The ocean subsystem is responsible for modelling and rendering the ocean. This includes visually simulating waves and the wake of each ship and providing each ship information about the current wave heights in its water plane area.

The network layer is intended to provide all communication between different instances of VirtualTrafalgar running on different machines over a network, allowing a multi user environment.

Simulation Evaluation

The 3D simulation environment has proven successful. Ships can be loaded into a scenario with sufficient data to allow them to respond correctly to the wind and user commands whilst maintaining fast, high quality graphics. On a modern laptop with a 2.8 GHz processor, frame rates of 45 frames per second have been achieved.

Wave generation techniques have been used to make the marine environment into a realistic user experience. The flexibility of the software architecture to allow different types of ship to be added has been achieved. This project has demonstrated a number of different Ship Plugins that are each capable of simulating a different type of ship.

The use of XML data files allows rapid creation of scenarios with many ships, and for entering ship data. The *Battle of Trafalgar* has been created as a scenario with each of the British, Spanish and French ships placed with an initial location and heading, as well as information about each ship such as name and length, see Fig. 16.

The physics engine implemented in the Generic Ship Plugin gives a good response to the wind when using the data collected for HMS Victory. When tested in a 15 knot wind, the simulation exhibits the behaviour shown in Figs. 17, 18,19.

Figure 17 shows the forward speed response of HMS *Victory* when filling all sails at an initial speed of 1 knot. The ship initially accelerates quickly, reaching 90% of full speed in 170 seconds. The full predicted speed of 9.52 knots is finally achieved in approximately 700 seconds. This top speed is a little above the expected top speed for *HMS Victory*, which has been cited to be 9 knots in a `good breeze' [3]. This could be due to a number of factors including that the simulation was run with a full suit of sails, while *HMS Victory* is likely to have furled some of the sails in a 15 knot wind.

Any sailing vessel must make some leeway when sailing across the wind. When beam reaching at 150^o degrees to the true wind, *HMS Victory* initially shows a large amount of leeway, as shown in Fig. 18. This is because the ship is blown sideways until the forward speed is such that the lift generated by the hull can counteract the sideforce generated by the sails. As can be seen, this occurs very quickly, with the maximum angle of leeway occurring within a couple of seconds of deploying the sails. The leeway then decays very quickly to less than 1 degree within 45 seconds. In comparison to the time taken to achieve full forwards speed, this is very low. This is very important during a tacking manoeuvre, as the ship will lose much of its forward momentum while turning through the wind.

The overall performance of HMS Victory is summarised in Fig. 22. Here, it is shown that with a single bracing angle of the sails, *HMS Victory* is very restricted in the angles she can sail at. When the sails are braced square to the ship, she is unable to sail closer to the wind than 150^o. On the other hand, if the sails are trimmed appropriately, the simulation predicts that *HMS Victory* would be able to maintain a good speed while sailing up to 110^o while carrying a full suit of square sails. Sailing closer than this would require that the square sails be furled, and staysails deployed.

Conclusion

This project has developed a realistic computer simulation of a Napoleonic era warship. In order to achieve this it has been necessary to conduct towing tank and wind tunnel tests to supplement existing technical information. The extent to which it has been possible to develop a realistic simulation and the theoretical and experimental conclusions that have been reached whilst doing this are outlined below.

It has been possible to produce a computer model of *HMS Victory* in the ShipShape program. Such a representation of the hull shape enables the future calculation of hydrostatic and seakeeping particulars relative to the vessel.

A 1.5 m towing tank model of the lower hull of *HMS Victory* was manufactured and successfully tested. A complete set of upright resistance estimates over the operational speed range has been produced. Whilst there is considerable scatter in this data at low speeds the general trend extracted from it is considered representative of the ship's actual resistance characteristics. Relationships have been derived that relate the effect of changes in leeway angle to the drag and side forces produced.

Unfortunately it was not possible to ascertain all the necessary manoeuvring derivatives from the towing tank tests conducted.. However, it has been possible to compare the two derivatives derived from oblique angle tests with semi-empirically derived manoeuvring coefficients. The similarity in orders of magnitude between the values derived by these separate methods suggests that the use of the semi-empirical formulae for the calculation of the derivatives is reasonable as a first approximation. The alterations to the derivatives under the influence of the rudder have been calculated from the experimental data.

A 1:40 scale wind tunnel model was successfully produced and tested with a range of apparent wind angles and speeds, sail configurations and sail bracing angles. Corrections for zero drift and blockage effects were applied to the measured data. The forces generated by individual sails, along with sail centres of effort, were then found from the differences in forces and moments produced by different sail configurations. This information was plotted as non-dimensional lift and drag coefficients against sail angles of incidence and regression lines were fitted where possible. The quality of these functions was evaluated and a number were selected to form the basis of the sail force models in the simulation.

Through the continued development of this software it is hoped that a tool will be produced to aid the study of Napoleonic naval warfare. The experimental data obtained may also be used in the design of modern square-rigged sail training vessels or replicacraft. The simulation has the potential to be used in the design or evaluation of other vessels, as well as for educational or training purposes

The eventual goal is a distributed web based environment with teams of individuals operating each vessel within the fleets. It is the interface between the user/s and the sail settings that will form the next stage of the project.

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