The *Art* and the Science of Naval Architecture in a Virtual Shipyard

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by Carl J. Harris

Naval Architecture has long been acknowledged as a blend of Art and of Science. However, it is only in recent years that the distinction between the Art and the Science has been so pronounced and so significant. Historically, the Art has always been well ahead of the Science, and in fact the success of the Art has generally predated the science by at least a century or two (if not more).

The Science is generally assumed to have begun with either Archimedes as the originator of the concept of buoyancy, or with Da Vinci with the first methodical studies of hydrodynamics. The Art began with the person who the first decided to sharpen the end of the log to make it easier to propel. The latter decision predated the scientific knowledge by many years, and probably took place in an arena far removed from ancient Greece.

With the advent of mechanical devices to allow quantitative measurements of basic parameters like towed resistance, things moved to a new level and 2-D plots of force versus speed became possible. Later, such quantifications became the norm and the Science began to expand from simple analysis of phenomena, to comparative studies of variations in a specific hull form. Progress along these lines picked up speed with the advent of computers a few hundred years later, and 3-D plots of cross-curve influences on multiple parameters became possible and the application of the Science took another big step.

It is crucial however to realize that the giants in our field: Smith with the *Marco Polo*, Roué with the *Bluenose* and Hereschoff with his many beautiful and graceful hulls, accomplished their masterpieces with very little input from the Science. Not to say that they were unaware of the advances of science, but their knowledge of the Art outweighed what was possible from the Science, and its availability, in their time. Advances in testing technology that proceeded on its own path had very little impact on what a Naval Architect did with the Science available, and even up to the late 1980s many senior NAs still relied on generic curves of form and rules of thumb to design the complex structure that is a ship.

In the modern world a ship is designed with a computer, using all forms of 3-D visualizations of form, and in-depth analyses of likely performance that would be incomprehensible to a Hereschoff – Science had taken the lead! But you will notice that there has not in recent years been a plethora of Naval Architects that are in the same league (as Hereschoff and others) in terms of the success of their designs, so Science alone is not the whole answer.

But that is enough of history, many others have written more and better than I on this topic - let's move away from design itself and jump forward to today and consider the modern implications of NA on the Art and the Science – and that juxtaposition is intentional. With the advent of simulation technology, the ability to provide (crew) training and feasibility analysis of a given hull in a particular situation, has gone in a few decades from a 2-D plot of a response curve to a full-mission/full-motion immersive experience that is fast approaching Virtual Reality.

The Naval Architect can now, in addition to the basic Art of designing the hull and equipment in reality, create a 'virtual' ship that within a simulated environment will respond realistically to human inputs. This is what in the industry is termed a (simulator) 'Ownship' (but for reasons I have never understood – if anyone knows the origin of this term I would love to hear it). But what is an *Ownship*?

An Ownship is essentially the ability to solve the equations of rigid-body motions in space coordinates and in real-time. These are not difficult equations to understand philosophically, and to solve them requires only that we know or can determine all of the external forces and moments, and at the same time know or determine all of the translational and rotational velocities. But that of course is the problem - aside from our

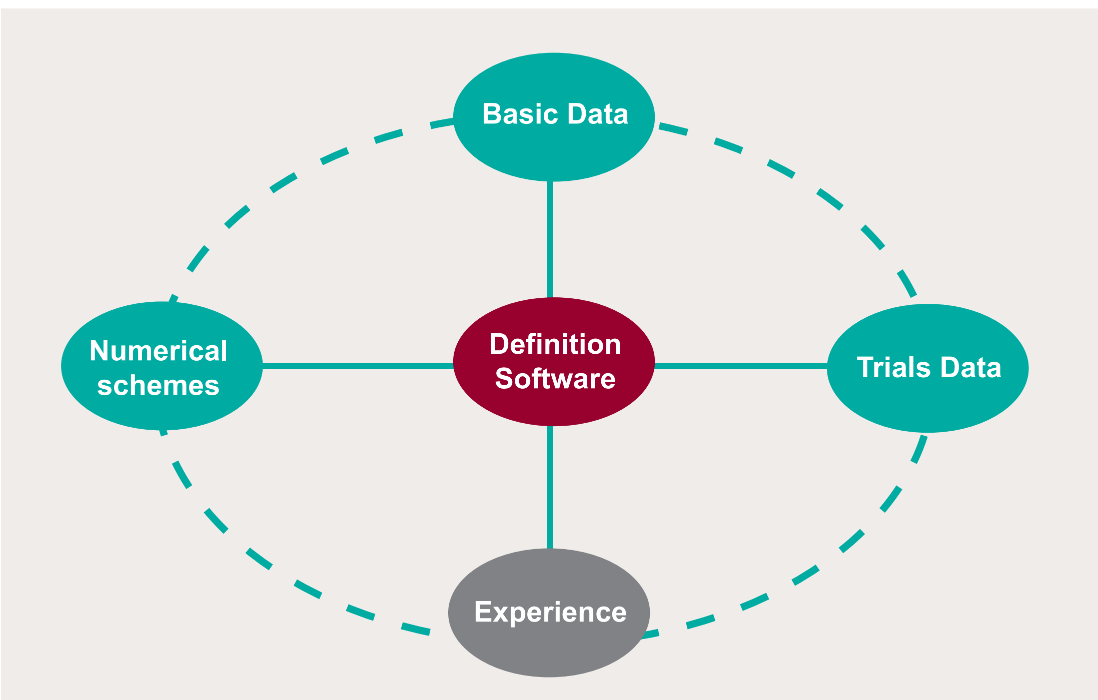

Figure 1. Conceptual Elements in the Ownship Assembly Process.

incomplete mathematical understanding of complex physical phenomena (especially when you add water), in order to achieve 'real-time' calculations requires that many physically complicated and non-linear phenomena be represented by much simpler equations with minimal inputs.

Figure 1 shows the conceptual elements in this assembly process and, over time, that process takes the form of the classic design spiral. Note if you will that if you replace the central element 'Definition Software' with say 'Roue' then you have the same elements that produced the *Bluenose*. And 'Experience' remains the basis on which the other elements rely. However, real-time simulation modeling has only been made possible by the dramatic advances in computing technology over the past decade or so. Even more recent advances in imaging technology and perspective graphics (and at CMS the addition of a motion-base) has now made simulation an accepted part of training standards worldwide, and the requirements of the Industry are increasing for more complex and elaborate simulation scenarios and human factor evaluations.

However, the basic science of ships and their behavior has not progressed at the pace of computer technology, and so we have a dilemma. The problem to be appreciated here arises from two sources:

a) The simulation subjects (i.e. Mariners) do not necessarily understand the limits and limitations of the science and technology that is used to show them 'their world', and hence misunderstandings have to be guarded against. But a Mariner often relies on his perceptive senses to make decisions, and hence his perception is his reality, or at least the framework in which he must operate.

b) The numerical model of the ship inside the computer (the assembly of curves and equations that represents the vessel within the simulation) is however not completely correct, in any sense of the word. Most things are simplified, some things unrealistically so, higher order terms/effects are ignored, and mathematically modeling true 3-D hydro/aero-dynamics in extreme conditions is still quite some ways off. It requires a balance and a blend of Art and of Science, with a healthy tempering of experience, to use such imperfect tools to produce a simulation environment that is realistic enough to have a value in training; and as Naval Architects we ignore this balance to our shame, and to the peril of those who go down to the sea in ships.

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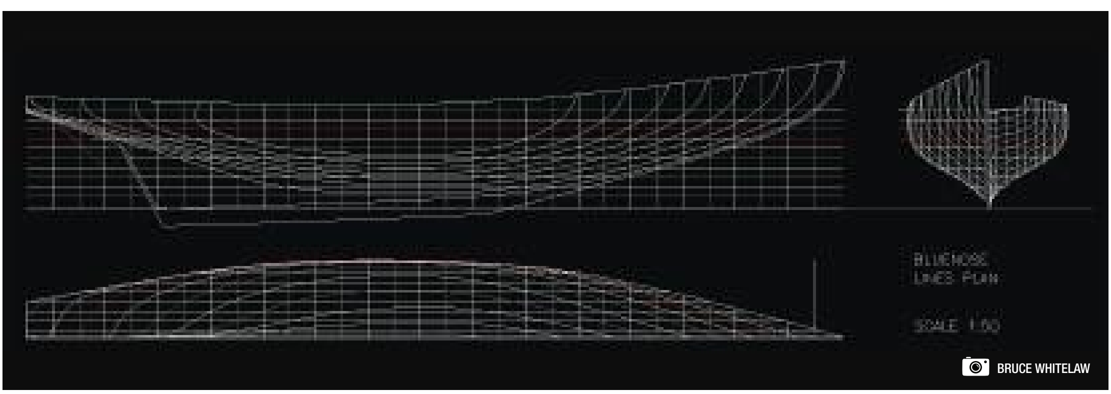

***Bluenose* lines plan.**

In the first instance, we must remember that it is the Mariner who actually knows what needs to be simulated in order that he get the correct visual/instrument cues, and a corresponding realistic response to controls. That can be achieved only if the person creating the simulation tools understands both what can be modeled, and more importantly what can't be modeled. The final truth for most things however actually lies somewhere between these two extremes, often with a collection of partial models that addresses discrete elements of the larger picture.

For example, on a ship being developed for routine bridge-watch training, we may use a method like Holtrop for estimating hull resistance, Isherwood for windage effects, Kajima for maneuvering behaviour and a Barras model for squat effects. Combining these diverse elements such that their combined outputs will generate a realistically behaving and mathematical model of a ship hull under power requires some juggling. Alternately, a virtual ship (generally for a port-development or feasibility study) will start from a collection of test-tank and wind-tunnel data along with a 3-D CAD model of the ship to provide shape data. In such a case, along with an appreciation of the limits of the modeling tools themselves, the designer must always keep in mind the inherent limitations of physical model tests – especially when the results are being combined to produce a final result. A test program can tell you a lot about your design, but it will also not tell you a lot that may be important in a comprehensive (simulator) model.

Aside from the obvious simplifications like a benign (testing) environment and limited test scope, there are other more insidious things to watch out for. For example, because of scale-effects, a free-running maneuvering model will not have the correct propeller RPM at the corresponding approach speed as measured in the towing tank. Thus, exactly matching performance from such tests will produce an incorrect result for the ship, at least to the degree that helm response is a function of propeller loading. So even with relatively 'exact' data to start from, the process requires critical judgment on how to include which pieces. That being said, there remain a lot of insights (on physical processes) that we still need from science to support that simulation art.

Another typical aspect of the designer's art in simulation comes when you really only have two points in space….or more precisely two temporal boundary conditions. The Art then comes in using judgment and experience, along with some first principles of Physics, to define how things progress from one state to another.

Consider a simple physical example:

- a tug connects its hawser to another ship - at this point the ship under tow will see only the weight of the hawser.
- The tug applies full power - the hawser now sees a load growing with time.
- At some point the load increase will cease and the combined ship/tug will achieve a quasi-static speed condition
- At this point the force component is at the level of the maximum available bollard pull from the tug.

So we now know two force conditions (start and end), and two speed conditions (start and end), and within a simulation's scenario the force-balance 'engine' just resolves the available forces to produce a final result over time. However should that (time) 'result' be deemed unacceptable, then the designer has a choice of what can be adjusted – tug power rates, ship resistance rates, tug wake fractions, hawser particulars etc. – at all times working towards matching the results of either full-scale trials or the acceptance of an experienced ship Master/Pilot. But even in such a simple/trivial case we need to be constantly aware of fundamental flaws that can creep in and become enshrined.

Perhaps I could explain this last comment a bit more by relating a recent incident. While working on some modeling scenarios for tug-assist, we (CMS) decided to compare a new tug that we had 'built', against a pre-packaged commercially available model. Starting with the commercial 65-tonne BP tug, I connected at the bow of a product carrier and called for 50 tons of pull at 015 degrees, gradually bringing up the wind on the beam to watch how the tug responded (in automatic mode) with changes to helm and power. Called away for a few minutes I decided to just let the simulation run and see how stable it would be over time.

Returning after about 25 minutes I was delighted to see that simulation still running with no errors. Motions were reasonable and the visuals were rock solid and very believable, right down to the spray at the bow of the tug. The vessel was still making way in the right direction, maintaining the requested 50 tonnes of pull within a percent or two, but unfortunately the 50 tonnes was now being applied at a speed over the ground of some 23 knots! The math model did not properly include the resistance of the tug in the balance of forces. This apparently is a 'known' problem for many instructors and is normally compensated for by the artistry of the simulator instructor (who interactively bleeds off available bollard pull as a function of speed). But this I fear is not a good practice as we are substituting Art in a case where there is sufficient Science. And as well we are shifting responsibility unto an instructor who has to try and compensate on the fly for something that we as Naval Architects can actually model quite well (at least to a sufficient level for a simulation.)

So when considering a simulator model, always look to see that the three Fundamental Laws of Engineering are satisfied (the second of which, in general form, is an Ownship). These Laws are written symbolically as:

1. $\sum_{i}^{n} \overline{F_i} = 0$

2. $\overline{F} = m \frac{d}{dt} \overline{v}$

3. 

Or descriptively as:

1. Statics - In a static situation the sum of all forces must equal zero.
2. Dynamics - The resultant force in a dynamic situation is the product of the mass and the rate of change of velocity.
3. Common Sense - You can't push a rope (or in this case deliver limitless power from a propeller.)

Recognizing a model that satisfies the first two laws may not be intuitive to the user, but the Third Law always is. Thus, while the creation of a realistic 'virtual' ship is a crucial part of any training/testing effort, and the use of synchronized near-real-life graphics is equally vital in a perceptive sense for the Mariner, the 'sex appeal' can sometimes obscure some things to a point where the lesson conveyed by the simulation is at best irrelevant and, at worst, dangerous.

So, how does such a group as diverse as Mariners, Instructors, Mathematicians, Graphic Artists and Naval Architects work together to get the most out of what is possible from simulation technology in training and in research? It is important that we get this right now, as anticipated advances (in both the Art and in the Science) will make simulations increasingly complex and demanding for all in the coming decades.

For a successful simulation project, it is important to start with a sufficient level of basic information and understanding amongst all parties - as much information as possible for the vessel scenarios (all ships and interactive objects), and a clear understanding of what is required from the simulation and what is not being represented (or represented incompletely) in the simulated scenario. For these reasons it is, I feel, vital that any simulation project team include a Naval Architect – for reasons of training the NA is more likely to understand the terminology and fundamentals of each of the other professions, at least to a level at which they can provide a 'translation' service; for an error in 'translation', from units of dimension, to sign conventions, to chart co-ordinates, is a constant pitfall waiting for the simulation team.

It is important that any numerical (simulator) model be carefully screened for the purposes intended. In my experience there are no complete simulator ship models, though all are correct at some level, and some are exquisitely elegant over a range of inputs. That being said, they will all break down if the user moves away from the regime in which it was built – this is quite often a speed issue, but generally extends to any extreme (of sea state, wind, current etc.) or any area of non-linear response (of the ship to the environment). The same can be said of the numerical modeling of the control systems (on the bridge) – controls technology has advanced much farther and faster then the tools commonly available to emulate them, and the result can be (for the mariner) either laughable (the best case scenario) or unrealistically difficult to master. This latter scenario, if pursued to a successful conclusion (for the student), suffices only to frustrate and not to teach.

The above general comments are most applicable to 'conventional' ships - a nominally streamlined shape with a propeller on a longitudinal shaft, and a rotating foil to act as a rudder. This is largely how a ship has (always) been defined for people of my generation (sailboats notwithstanding), and is what is assumed when groups like IMO formulate performance guidelines.

However advances in ship design (i.e. the X-Bow and Azipods to name a few) simply do not fit into conventional 'wisdom' (and the ludicrously low L/B ratios of some fishing vessels fit into 'no wisdom at all') and thus we are faced with a situation wherein a numerical designer is using incomplete data and working (perhaps) with incompatible tools on a design for which conventional guidelines of performance can not be applied directly. Combine such elements and then imagine using the result to deliver realistic training that will prepare the mariner for the actual ship. Given the awesome ingenuity of some simulator instructors, such may be possible, but it is by no means guaranteed - by either the Art or the Science of the Naval Architect.

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