A Simulation of Interactions Between the Critically Endangered North Atlantic Right Whale *Eubalaena glacialis* and Shipping using Dynamically Variable Temporal Granularity to Minimise Run Time

H.Clyne and J.Kennedy

School of Computing, Napier University, Edinburgh. h.clyne@napier.ac.uk

Abstract: Collisions with vessels are a major cause of mortality for the severely endangered North Atlantic right whale *Eubalaena glacialis*, with the total population currently numbering only around 300 individuals. Although having a great impact upon the chances of survival of the species, right whale/vessel collisions are a rare event, possibly only in single figures over a whole year. This simulation aims to give an insight into potential levels of risk associated with different vessel speeds and proximity to whales. The modelled whale movements and interactions with shipping are based upon field data of right whale movement and incorporate some assumptions about right whale behaviours. The utility of the simulation is clearly dependent upon this input data, but even with some behavioural assumptions and poorly specified input, is expected to provide a better understanding of the interactions between right whales and vessels. The rarity of interactions between whales and vessels requires several years to be simulated to produce sufficient collisions to draw conclusions about the effects of any changes to parameters. The crucial interactions between whales and vessels are required to be modelled with small time intervals but for the great majority of simulation run time such fine grain movement is unnecessary and would result in large simulation run times. Run time is greatly reduced by the use of dynamic variable temporal granularity to provide the maximum possible time interval for every step on a step-by-step basis.
It is intended that the simulation data could be used in an attempt to draw conclusions as to the most effective advice to be offered to shipping moving through an area where right whales are known to be present.

Keywords : Simulation; *Eubalaena* ; North Atlantic right whale; Dynamic variable temporal granularity

1. INTRODUCTION

The North Atlantic right whale *Eubalaena glacialis* (figure 1), a large baleen whale, is among the most endangered of all large whale species. Despite more than six decades of international protection following hunting to the point of extinction the population shows no sign of recovery. Under current conditions the population is doomed to extinction [Caswell et al., 1999]. Knowlton et al. [1994] concluded that total mortality in the North Atlantic is possibly double what it would be without human interference. Reducing the human-caused mortality is essential to the viability of this population.

In addition to mortalities caused by entanglements with fishing gear, behavioural characteristics and habitat preferences mean these slow moving whales may be more vulnerable to vessel strikes than other species of great whale [IWC, 1998].

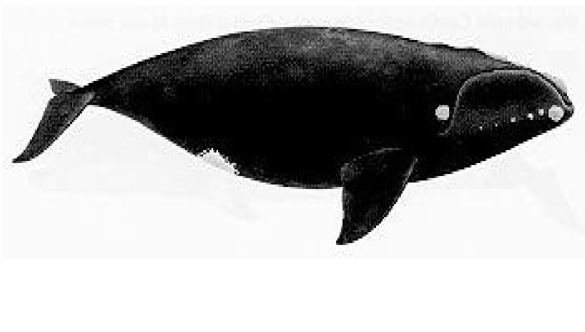

Figure 1. The North Atlantic right whale *Eubalaena glacialis.*

Any reduction in human induced mortality may be enough to swing the balance far enough in the right whale's favour to allow the population to begin to increase. There is pressure upon the shipping industry to try to minimise vessel strikes.

In an attempt to reduce the likelihood of collisions, current advice to mariners transiting areas where right whales are suspected to be present is to post a lookout and reduce vessel speed. Efficiency of such measures relies upon being able to see any whale in the path of the vessel and in the vessel's ability to manoeuvre to avoid a collision. However, right whales are only visible on the water surface and then only where conditions allow. A vessel transiting an area at lower speed will give a whale more time to respond but may have a reduced manoeuvrability and will remain in the critical area for a longer period of time. Should a whale not take avoiding action then there may be an increase in the probability of a collision occurring between the vessel and a whale.

In reality, fatal interactions between vessels and right whales are rare events, possible occurring in single figures annually. Field data on behaviours of right whales in the presence of vessels is almost non-existent and there are limited data on factors leading to a fatality.

This paper describes a simulation developed in an attempt to investigate the sensitivity of the effectiveness of mitigation measures to the assumptions that were made when designing these measures. Analysis of output may be incorporated when investigating the most effective advice to be offered to shipping in the presence of right whales.

Collision rates for vessels of varying speeds and characteristics travelling through an area of right whales moving in three dimensions are explored. Right whale movements are modelled upon field data from a variety of sources and incorporate some assumptions about behaviours.

Run time has been reduced by setting the simulation time step as large as possible for each and every step. This dynamically variable temporal granularity introduces an element of event orientation to the otherwise fully interval orientated method used to represent time and has resulted in a significant reduction in run time.

2. WHAT'S WRONG WITH THE RIGHT WHALE?

Formerly abundant and widely distributed in the North Atlantic "the right whale to hunt", was hunted as early as the 10th century [Reeves and Mitchell 1986] with the population commercially depleted by the mid 1700’s [Hamilton and Mayo, 1990]. Northern right whale population status and movements have been extensively studied in the western North Atlantic and although a whaling ban on right whales has been in place since the mid 1930’s, only about 300 individuals survive [Caswell et al., 1999]. These are found mainly in the western Atlantic between Nova Scotia and Florida [Kraus et al., 1986]. This low population is in contrast to the Southern right whale *Eubalaena australis*, where population modelling suggests a recovery from about 300 surviving animals in 1920 up to a mid 1990’s estimate of several thousands [IWC, 1998].

18 out of 50 known North Atlantic right whale deaths between 1970 and 2001 were caused by vessel strikes. It is likely that this is an under-estimate since not all carcasses were recovered and necropsies in earlier years may not have been sufficiently thorough to rule out vessel strike as a cause of death. [IWC, 2001] An estimated 47% (8/17) of all North Atlantic right whales known to have died between 1991 and 1998 have been attributed to collisions with vessels [Knowlton and Kraus, in press]. The North Atlantic right whale Consortium Catalogue suggests about 20 vessel-struck whales which are known to have survived [Kraus, 1997].

2.1 Right Whale Behaviours

Based upon field observations there are five generalised categories of whale behaviour. Each of these behaviours will have an effect upon the chances of a whale encountering a vessel, and upon the likelihood of the whale taking avoiding action, or of the vessel seeing the whale.

- Logging: The whale floats motionless, possibly sleeping.

- Surface feeding: slowly swimming, large mouths open, filtering plankton, never below a depth at which they may be struck by vessels.

- Deep feeding: surfacing to breath and then deep dive. Virtually no predictability of surfacing position.

- Travelling whales: Typically long shallow dives, travelling for miles in one direction but with occasional changes in direction without the reason necessarily being apparent. Such a whale may remain within a depth at which it could be struck by vessels.

- Socialising whales: Surface Active Groups are in a tight group engrossed in social activity (mating!). More visible than a single whale and more likely to be seen by a vessel, visibility allowing.

Observations of right whales engaging in social behaviour, nursing or skim feeding [Mayo and Marx, 1989] suggest they make no effort to avoid the approach of small boats but data on responses to larger vessels remains scarce.

3. MODELLING WHALES

Models involving whales with most relevance to this simulation have been applied to analysis of line transect survey methods to estimate whale populations [Hiby, 1982; Turnock and Quinn, 1991; Schweder et. al., 1997]

More commonly models involving whales have been population models exploring effects on populations by whaling [International Whaling Commission, 1994] and effects on fisheries by whales [Markussen, et al., 1992].

Long time scale sperm whales movements over large distances, in two dimensions, have been analysed by applying mathematical models to mark and recapture data [Whitehead, 2001].

The *Virtual Whale Project* visually reproduces three dimensional whale movements and sound visualisation of bubble structures based upon movement data and sounds recorded during humpback whale bubble feeding [www.cs.sfu.ca/research/projects/Whales]. Whilst *The Virtual Whale* at first seems similar to this right whale simulation, the animated virtual whales do not move as a result of produced movement data but is rather a tool to visualise short term field data.

4. THE SIMULATION

At the most simplistic level, the simulation consists of spherical objects moving in three dimensions according to a set of parameters interacting with brick-shaped objects moving in two dimensions.

The Object-Orientated model is built around the concept of individual ships and whales as objects with their own behaviours moving in an environment determined by a set of selected parameters.

The simulation is written in Java, in part to be machine independent, and runs on any standard PC. For efficiency of speed, there is no graphical output.

Positions of whales and ships are maintained in Cartesian co-ordinates. Output of the simulation records the times and positions of collisions, and type of collision that occurred. Each collision is further identified as having occurring with the bow, stern, side or bottom of the ship.

There is an almost limitless set of variables and components that could be incorporated when attempting to model the biological system that affect positions and behaviour of whales. Identifying, selecting and understanding the critical components of the system suggests that the more detail used, the more realistic the simulation may become. However, interpretation of the output for a simulation based upon a more intricate model becomes more difficult with increased complexity. Initial simplicity of environmental modelling allows exploration of the effects of changing specific individual parameters.

4.1 Whale Body Representation

The rather rotund right whale body can be reasonably represented as a sphere.

4.2 Whale Movements and Distributions

Dependent upon the selected behaviour of the simulated whale, the movement parameters; e.g. maximum and minimum speeds through water, distances travelled, depth of dives, times whales can spend under water, times whale must spend breathing/resting and proportions of dives, are taken from probability distributions based upon field data.

4.2.1 Whale vertical movements

The simulated whales move in three dimensions following a dive cycle appropriate to the selected behaviour (Figure 2). Proportions of each dive are related to the length and depth of that dive cycle.

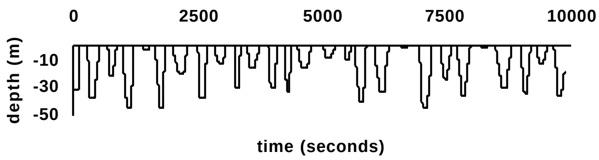

Figure 2. Simulated diving cycles.

4.2.2 Whale horizontal movement

The speed of travel of the whale is related to the whale behaviour below water. Where a whale is diving steeply or surfacing, the horizontal speed of travel is reduced.

4.3 Whale Responses to Vessels

The majority of the whale movements in response to vessels are based upon assumptions. Inferences based upon the results of any simulation run are referenced to the set of assumptions used for that run.

The three avoiding actions simulated are:

- diving when close to a vessel
- swimming directly away from a vessel
- taking the best avoiding route possible

As more data on whale responses to vessels becomes available this can be incorporated.

4.4 Distribution of Whales

The density of 50 whales in a 10 km x 10 km area used for initial simulation runs are derived from observations made in the Bay Of Fundy (US/Canada) where groups of whales congregate in the summer months. This represents a high risk area for Northern Right Whales, due to the presence of a busy shipping lane, running approximately North / South down the middle of the lower bay, which is about 60 miles across at this point.

To maintain whale numbers within the simulation, where a whale leaves the edge of the simulation box another is generated at a random point on the boundary

For other geographic areas, different whale distribution patterns are required to be modelled. For example, the situation in Florida in springtime involves less concentrated mother and calf pairs in shallower waters.

4.5 Representation of Vessel Hull

The representation of a vessel hull within the simulation is that of a block. The computational cost is high in modelling a more elaborate hull and in determining collision information with reference to that shape. The retention of the centre positions and heading details for each collision using this generalised hull representation allows further investigation of the hydrodynamic effect of a more complicated shape to be applied to the output data.

4.6 Vessel Speeds

For each vessel, realistic ranges of speed are simulated across the possible speed range. Generally, this is in the region of 15 different speeds. Following initial runs generally a range of speeds emerge to be looked at in greater detail.

4.7 Vessel Reactions to Whales

At different speeds, individual vessel types have particular manoeuvrability characteristics. Incorporating these within the simulation can explore the effectiveness of different tactics employed to minimise the numbers of collisions upon sighting whales.

5. DYNAMICALLY VARIABLE TEMPORAL GRANULARITY

The incidences of collisions produced by the simulation are rare. As a result, one of the problems that arose in the development of the simulation was the long time to run to provide sufficient data for analysis. This was in spite of attempts to reduce run time by use of techniques such as optimisation during compilation and using constants rather than variables where feasible.

Addressing the problems of the slow running speed of the simulation led to the conception of a method to reduce the time step used for the great majority of the simulation run-time. When there are interactions occurring, these are required to be modelled in fine detail and a temporal granularity of one second allows small-scale movement. For the majority of the time the distances between whales and vessels are too great to provide any such interactions. These periods of simulation are irrelevant in all but the frequency that the interactions occur. Whilst the behaviours of whales and speeds of whales and vessels must remain unaffected, larger time steps reduce the numbers of steps required and therefore decrease run time.

In order that the temporal granularity should be varied to provide the most efficient time step used for each and every step, the concept of dynamic variable temporal granularity has been developed.

The largest possible time step that could be used without potentially producing an interaction between vessels and whales is determined for each move.

The vessel determines the distance and bearing relative to current vessel heading for each whale. The maximum time step that can be used to travel by the vessel and by that whale without leading to an interaction is determined. In this process "worst case scenario" is used, i.e. it is assumed the whale will travel at full speed and take the route most likely to produce an interaction with the vessel. The special case of the whale re-entering the box during a move is taken into consideration and treated as a possible interaction event.

This process is repeated for each of the whales in the simulation and the smallest time step derived is used to move the vessel and each of the whales.

6. DATA SOURCES

There are several published studies of movements of right whales and a large quantity of unpublished movement data.

Data on horizontal movements of whales, based upon surfacing positions, are more common than vertical data as visual techniques may be used. The proportion of time the whale spends on the surface, sea-state, weather conditions and amount of light available impose limits on the functionality of visual techniques. This also provides little information about the horizontal or vertical movements of whales when below water.

6.1 Tagging Whales

Sources of relatively fine-grain movement data include movement studies carried out with the use of electronic tagging devices that may provide movement data from below the water surface. Tags may be attached in some way to the body of the whale (stuck into the whale's body or by using a sucker attachment) but generally provide only limited time periods of data as the tags become dislodged or fail. Other tags have been attached where whales are trailing ropes or fishing gear. In both these tagging methods it is to be noted that the whale has probably been stressed in some way, by the entanglement and/or the tagging procedure, and it is possible that this will produce behaviour effects.

6.2 Other Whale Movement Data

Other information on depths of dive are available where it is known that the whale is travelling to the sea bed, for example where they are seem to have mud on their heads following a dive. Where the sea is shallow this obviously places a limit upon any possible dive depth.

Complex field techniques are involved in plotting the movements of a whale where the recording of whale positions are made relative to a moving platform of observation such as a vessel [Leaper, et.al, 1999]. However, such movement data is less likely to have been influenced by the method used for recording.

6.3 Ship Data

Shipping dimensions used for larger vessels within the simulation are obtained from *the Lloyds register of shipping*. Some simulation vessel movements are based upon field data from the Bay of Fundy [Leaper, et.al, 1999]. Manoeuvrability of shipping is available from a variety of published data [e.g. Rawson and Topper, 1991].

Five different vessel types have been selected as representative for the areas under investigation:

- Fishing boat
- Container vessel
- Super tanker
- Ferry / small cargo vessel
- High speed ferry

7. CONCLUSIONS

Given the lack of field data on the interactions between whales and vessels, there is value in the way this simulation can be used to repeatedly route vessels with different avoidance strategies through areas of right whales in a way that is not possible (or desirable) in reality. The sensitivity of different avoidance measures can then be investigated without putting real whales at risk.

The limited data available on whale responses to vessels is a small sample size and not necessarily representative of whale behaviour but is the best currently available. The simulation can only at best reproduce a gross simplification of the complex biological system driving whale movements and many assumptions are made about the movements and responses of whales. Simplification of the system does however mean that effects within the simulation are more likely to be as a result of changes in the parameters under investigation rather than other processes.

Dynamically variable temporal granularity may prove to potentially introduce unpredictability into more complex processes such as randomly heading whales or whales involved in grouping behaviours. As the maximum step size possible before an interaction may occur becomes smaller with increasing complexity of interaction, the computational costs of determining the size of that step may lead to the simulation running slower than simply using the default step size.

The use of dynamically variable temporal granularity substantially reduces simulation run time where modelling individual whales moving with simple behaviours and the use of the changing time step has no significant effect upon the simulation output.

8. REFERENCES

Caswell, H., M. Fujiwara and S. Brault, Declining survival probability threatens the North Atlantic right whale, *Proceedings of the National Academy of Sciences* 96, 3308-3313, 1999.

Hamilton, P.K. and C.A. Mayo, Population characteristics of right whales (*Eubalaena glacialis)* observed in Cape Cod and Massachusetts Bays, 1978 - 1986, *Report of the International Whaling Commission* (Special Issue) 12: 203 - 208, 1990.

Hiby. A.R., The effect of random whale movements on density estimates obtained from whale sighting surveys, *Report of the International Whaling Commission* 32: 791-793, 1982.

International Whaling Commission, Report of the Workshop on the Comprehensive Assessment of Right Whales: A Worldwide Comparison, *SC/50/REP 4*, 1998.

International Whaling Commission, Report of the scientific committee meeting, London, 2001.

Kraus, S.D., J.H. Prescott, A.R. Knowlton and G.S. Stone, Migration and calving of right whales (*Eubalaena glacialis*) in the Western North Atlantic, *Report of the International Whaling Commission* (Special Issue) 10: 139-144, 1986.

Kraus, S.D. Right whale status in the North Atlantic. Shipping/Right whale workshop. A New England Aquarium Aquatic Forum, 17-18 April 1997. A.R. Knowlton, S.D. Kraus, D.F. Meck and M.L. Mooney-Seus (eds), Series Report 97-3, 31-36, 1997.

Knowlton, A.R., S.D. Kraus and R.D. Kenny, Reproduction in North Atlantic right whales (*Eubalaena glacialis), Canadian Journal of Zoology* 72, 1297-1350, 1994.

Knowlton, A.R. and S.D. Kraus, Mortality and serious injury of northern right whales (*Eubalaena glacialis*) in the western North Atlantic Ocean, *Journal of Cetacean Research and Management*, 2001.

Leaper, R., A. Moscrop, N. Biassoni, S. Brown, H. Clyne and R. McLanaghan, Use of a combined compass and binocular system to track the movements of whales and whale watching vessels, Presented to Scientific Committee meeting of the International Whaling Commission, Grenada, 1999 SC/51/WW10, 1999.

Markussen, N.H, M. Ryg and C. Lydersen, Food consumption of the NE Atlantic minke whale (*Balaenoptera acutorostrata*) population estimated with a simulation model, *ICES Journal Marine Science* 49 317-323,1992.

Rawson, K.J. and E.C. Topper, Basic Ship Theory 2, Longmann Scientific and Technical. 1991.

Reeves, R.R. and E. Mitchell, American pelagic whaling for right whale in the North Atlantic, Pp 221 In: R. Brownell, P.B. Best and J.H. Prescott, (eds), Right whales: past and present status, *Report of the International Whaling Commission* (Special Issue) 10: 1986.

Schweder, T., H.J Skaug, X.K. Dimakos, M. Langaas and N. ∅ien, Abundance of northeastern Atlantic minke whales, estimates for 1989 and 1995, *Report of the International Whaling Commission,* 47: 453-485, 1997.

Turnock, B.J. T.J and Quinn, The effect of responsive movement on abundance estimation using line transect sampling, *Biometrics,* 47, 701-715, 1991

Whitehead, H. Analysis of animal movement using opportunistic individual identifications: application to sperm whales, *Ecology,* 82(5) 1417-1432, 2001.