Project 3 – Modeling Whale Entanglement Events (NEAq, Duke University, Bellequant Engineering)

Project Goal and Objectives

In the absence of direct observations of entanglement events involving baleen whales, the goal of this project was to better understand the dynamics of rope entanglements by drawing from hydrodynamic modeling involving actual and computer models.

Project 3 Final Report

Modeling Right Whale Entanglement Events

Laurens E. Howle, Ph.D., P.E., F.ASME
BelleQuant Engineering, PLLC
7813 Dairy Ridge Rd.
Mebane, NC 27302

Doug P. Nowacek, Ph.D.
Nicholas School of the Environment &
Pratt School of Engineering
Duke University Marine Laboratory
Duke University
Beaufort, NC 28516

Executive Summary

This final report summarizes our progress in generating an interactive virtual computer modeling system that will allow marine mammal scientists to reverse engineer entanglement events between whales and fishing gear. Although this is an ongoing project, this report summarizes our work under ending NOAA grant number NA09NMF4520413. As of the date of this report, we have completed the following tasks[1]: (3) research rope – cable models, (4) code FD/FE rope – cable models, (5) test rope model interaction with existing whale model, (8) install and learn Blender software, (9) compile a basic list of NARW motions, (10) create NARW bone mesh, (11) create NARW skin mesh, (12) code NARW motions, (15) install and test nVidia PhysX API, (16) code whale kinematics models (NARW), (17) code, test, refine, and optimize collision models, (20) generate and code whale – rope friction model. The first major task group, (2) <u>Rope Model</u>, the second major task group, (7) <u>NARW Animation</u>, and the third major task group, (14) <u>Collision Model</u>, are all 100% complete. The fourth major task group, (19) <u>Friction Model</u>, is 49% complete. Additionally, we were able to locate an open source software package to replace the commercial package we had originally budgeted for this project.

Abstract

The North Atlantic right whale (*Eubalaena glacialis*) is critically endangered. Population estimates put the number of North Atlantic right whales (NARW) in the range of 350 individuals with some indication of a slight upward trend [1]. The National Marine Fisheries Service (NMFS) has designated the summer feeding and nursing areas of Cape Cod Bay and Great South Channel as critical habitat areas. Several of the NARW

---

[1] Task #s refer to those in the chart (Figure 3-7).

areas are also productive for lobster and other fisheries. Entanglement of NARWs with lobster and other fishing gear is a major cause of mortality in the population (ship strike is another major cause of mortality) [2]. One recent study using photo-identification of NARWs found that greater than 75% of the NARWs had been entangled at some time in their lives and many NARWs had been entangled numerous times [3]. While there are many case reports on post entanglement and entanglement severity [2], there remains little documentation of first-encounter and how NARWs or other baleen whale species, such as the humpback whale (*Megaptera novaeangliae*) [4], become enwrapped after a first encounter with gear. In order to gain a better understanding of how entanglements might occur, and to aid in the analysis and design of fishing gear, we have developed an interactive simulator that allows the user to swim a virtual whale model through a gear field in an attempt to recreate (or reverse engineer) an entanglement given post-entanglement field observations or necropsy reports. Our entanglement modeling system is capable of running on either a PC or an Xbox 360 gaming console and uses a morphologically accurate whale model [5].

Introduction

The North Atlantic right whale (*Eubalaena glacialis*) has been fully protected from commercial hunting since 1935, but the species is still listed under the U.S. Endangered Species Act and as Critically Endangered on the International Conservation Union (IUCN) 'Red List'. The number of animals in the species does appear to be slowly increasing [1], though continued serious injury and mortality from ship strikes and entanglement in fishing gear are certainly still slowing the recovery of the species [1, 3]. Becoming entangled in fishing gear is dangerous for whales for several reasons. Direct mortality from gear has been documented, but more common is the gradual decrease in body condition associated with gear being wrapped around body parts, including the mouth, reducing the animal's ability to feed [2, 6]. Even when not involving the mouth, entanglements force animals to expend as yet unknown amounts of additional energy as they drag gear through the water.

To address the injury and mortality from ship strikes, several measures have been taken such as the shifting of shipping lanes in the U.S. and Canada and the recent implementation of a speed reduction rule around ports along the U.S. east coast. In an attempt to reduce entanglements in U.S. waters, the National Marine Fisheries Service implemented a rule requiring that lines joining fishing traps along the bottom must be neutrally or negatively buoyant (i.e., so-called 'floating' line is believed to entangle whales as they swim close to the bottom to feed) [7]. Even with the reduction of this threat, there are still thousands of lines in the water associated with traps as the ropes connecting the trap lines to the surface number in the hundreds of thousands. Another means of addressing the entanglement problem is to remove the gear from an entangled whale, an operation that is expensive and dangerous for both whales and humans. Even with the successful removal of gear, animals can carry life-long injuries [2], whose fitness consequences are poorly understood. Also, while disentanglement is sometimes successful, many more animals become entangled than can be helped and many entanglements are known to us through the existence of scars from previous entanglement events [3].

Given the prevalence of entanglement, its detrimental effects to the whales and the difficulties of treating the animals once entangled, the best strategy seems to be to prevent whales from becoming entangled. One way of preventing entanglements is to remove the gear from the water, and some measures have been taken to do this, but there is still a staggering amount of line in the water. Another strategy is to design gear that minimizes the chances that a whale will become entangled when it encounters the gear. In this vein there are been attempts to make different types of rope, or rope that disintegrates in a relatively short period of time, or rope that is somehow easier for the whales to detect. The method we have taken to contribute to this search for solutions is to recreate the sequence of events that lead to entanglements and to ‘reverse engineer’ the situation in hopes of gaining insight into some changes that can be made to the gear to reduce the likelihood that a whale will become entangled when it does encounter gear in the water. We have created a virtual whale entanglement simulator (VWES) to do this, and this environment also returns information on the forces (e.g., frictional, drag) experienced by the whale and the gear during an encounter. We report here on the second version of the ‘virtual whale entangler’, its outputs and directions.

Nomenclature

API	Application programming interface
CPU	Computer processing unit (computer hardware)
GPU	Graphics processing unit (computer hardware)
NARW	North Atlantic right whale
NEAq	New England aquarium
NMFS	National Marine Fisheries Service
NOAA	National Oceanographic and Atmospheric Administration
SAG	Surface active group
VWES	Virtual whale entanglement simulator
XNA	Microsoft managed DirectX API

Methods

Early in the development process for our VWES, we investigated several APIs for displaying the graphical output from the VWES system. Two of the more popular graphics APIs are OpenGL and Direct3D [8]. Direct3D was developed by the Microsoft Corporation and is a proprietary API for use with the Windows operating system. OpenGL was originally created by the Silicon Graphics Corp. and has become a widely-used open standard API. Both of these graphics APIs will take advantage of hardware acceleration if the capability exists on the computer's graphics card [8]. A third graphics API set, XNA, is a proprietary Microsoft system that provides a managed wrapper for the Direct3D and DirectX API sets [9-14]. XNA is the API most frequently used to program Xbox 360 and many Windows games. The XNA API set offers many advantages to the programmer when developing graphics-intensive applications such as native integration with the managed C# computer programming language. After a thorough review of these competing graphics APIs, we selected the XNA API set for graphics programming.

Although one paper documents the entanglement of the juvenile humpback whale with a fishing net [4], little is known about the behavior of whales when they encounter trap gear and how they become entangled after first encountering the gear. One of our goals in developing the VWES we discuss in this report is to generate a virtual system that marine mammal scientists can use to reverse engineer whale entanglement events. An additional motivation for this work is to create a virtual gear design software system which fishing gear designers and Marine Fisheries regulators can use to virtually test gear modifications before resorting to more expensive and time-consuming field tests. This could help the designers and regulators reduce the probability and/or severity of whale entanglement. In planning the development of the system with scientists at the NEAq and the NMFS, we decided that the most useful tool for our VWES is an interactive system that allows the researcher to control the whale’s movement and test various “what if” scenarios. The XNA 4.0 Game Studio programming API provides a natural solution to our requirements. Another advantage of developing under the XNA API is at the modeling system can be deployed to either computers running Microsoft operating systems or to the Xbox 360 game consoles.

We developed our VWES so that the user controls the whale's movements using a standard Xbox 360 game controller. Currently, the whale dynamics are kinematic while the gear dynamics are kinetic. That is, the whale's movements are prescribed by the user without regard to the forces needed to generate those movements whereas the trap gear reacts to interactions with the whale and with the surrounding environment. In further refining our VWES, we will give the user the option of kinetic/kinetic dynamics. User input with the controller is as follows: whale swim speed is controlled by the left trigger; pitch and roll are controlled by the left joystick; left and right yaw are controlled by the right joystick; fast (cheat) swim speed is controlled with the right shoulder button; the start button restarts the simulation; the back button exits the program; the B button toggles first or third person (whale) point of view; and the Y button enables weak links to break the trap line if the line tension exceeds a set value. Additionally, the controller gives feedback to the user by vibrating if the whale collides with the seafloor, with another object, or attempts to breach the ocean surface.

The kinetic behavior of the gear and collision detection turned out to be one of the major areas of effort for this project. After much programming effort of the kinetic gear behavior and collision detection, we elected to use a commercial, off-the-shelf (COTS) game engine physics API [15] that included kinetic physics models, collision detection, and many other physics simulation capabilities. While other physics engine systems are available [16], the COTS game engine API that we chose was particularly well suited to this project due to its low cost, relative ease of programming, and the fact that this API did not require specific video hardware to operate efficiently. We also investigated the use of the nVidia PhysX game engine [17]. However, we decided not to use this game engine due to the fact that it includes native support for only the C++ programming language and does not include native support for the C# programming language. Therefore, we decided to continue to use our COTS game engine.

The 3-D right whale used in our VWES was created in several steps. First, a gaming programmer created an initial wire mesh whale in Lightwave, basing the shapes and dimensions of the whale parts on pictures and video. That model was then imported into Modeler Pro, where it was substantially revised it using empirical measurements obtained from necropsy reports and from photogrammetry efforts (for full details see [5]. After updating the 'base' model whale, we also created a pregnant whale model and a version with the whale's mouth open as it would be for feeding. In Figure 3-1, we show the open mouth and closed mouth versions of the North Atlantic right whale model used in our VWES.

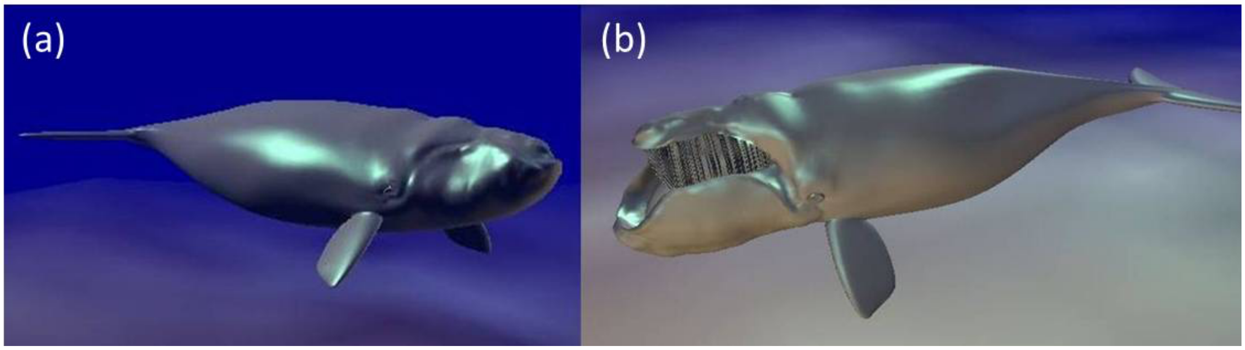


Figure 3-1. Closed mouth (a) and open-mouth (b) versions of the North Atlantic right whale used in our Virtual Whale Entanglement Simulator (VWES).

Much information on the properties of ropes such as strength, bending stiffness, elongation, friction, and wear due to internal and external damage is available in the literature for fiber [18-20] and wire [21, 22] ropes and will not be reviewed here. In this section, we will focus the discussion on the specific issues we faced with the rope and gear models used in the VWES. We begin with a discussion of static rope models. This is followed by information on the dynamical modeling of ropes under varying loads and with possible frictional contacts.

Solutions for the static shape of a rope under the effects of general body and surface forces are well-known and readily available [23]. We initially used these model solutions in the VWES for specifying the initial rope shape for some of our simulations. Later, we found it more practical to specify a simpler initial shape and let the rope settle to a steady-state configuration under the combined effects of current, buoyancy, and possible contact with other objects such as traps. Measurements of floating ground line elevation are also available [24] but we did not use this information in the VWES due to the fact that floating ground lines are not currently used in fisheries. We also built in the capability to have multi-part ropes into the modeling system. This allowed us to model the use of a floating endline portion connected to the trap and a sinking endline portion connected to the surface buoy.

The dynamic simulation of ropes (endlines, gangions, groundlines) is a subject that occupied a large fraction of our efforts for this project. Fast and accurate simulation of rope dynamics with time varying loads and time varying contacts is an active area of current research focus, particularly in the offshore structures [19, 20, 25, 26], and computer graphics [27, 28] fields. Some of the issues that one faces in generating an accurate rope model for interaction with other objects include the need to balance computational speed, accuracy, and stability. Rope models can generally be classified into two categories, continuum models and models that approximate the rope as a chain of rigid bodies [27]. In our VWES, we used the second of these two approaches. That is, we approximated the continuous rope by a series of rigid bodies, either spheres or cylinders, which were connected to one another with virtual springs. The springs allowed the force to be transmitted from one link component to the next and allowed for relatively easy collision detection calculations. However, if the spring constant was too large, the dynamic rope became unstable. Additionally, the use of spring connectors allowed the VWES to simulate weak links by specifying a spring tension force at which the link would break. An image from the VWES of the dynamic rope model along with and entangled NARW is shown in Figure 3-2.

Gear models used in the VWES consisted of traps, lines, and buoys. The trap models were approximated by rectangular boxes having all of the mass concentrated on the outer surface. This allowed the correct mass moments of inertia to be calculated so that the physics simulation involving the traps was more accurate. Additionally, collision detection between the rope and the traps was appropriately handled. In addition to the trap model we also used a buoy model in our simulations. The buoy model appropriately handled the physics calculations that resulted from its buoyancy and the hydrodynamic drag from an imposed current.

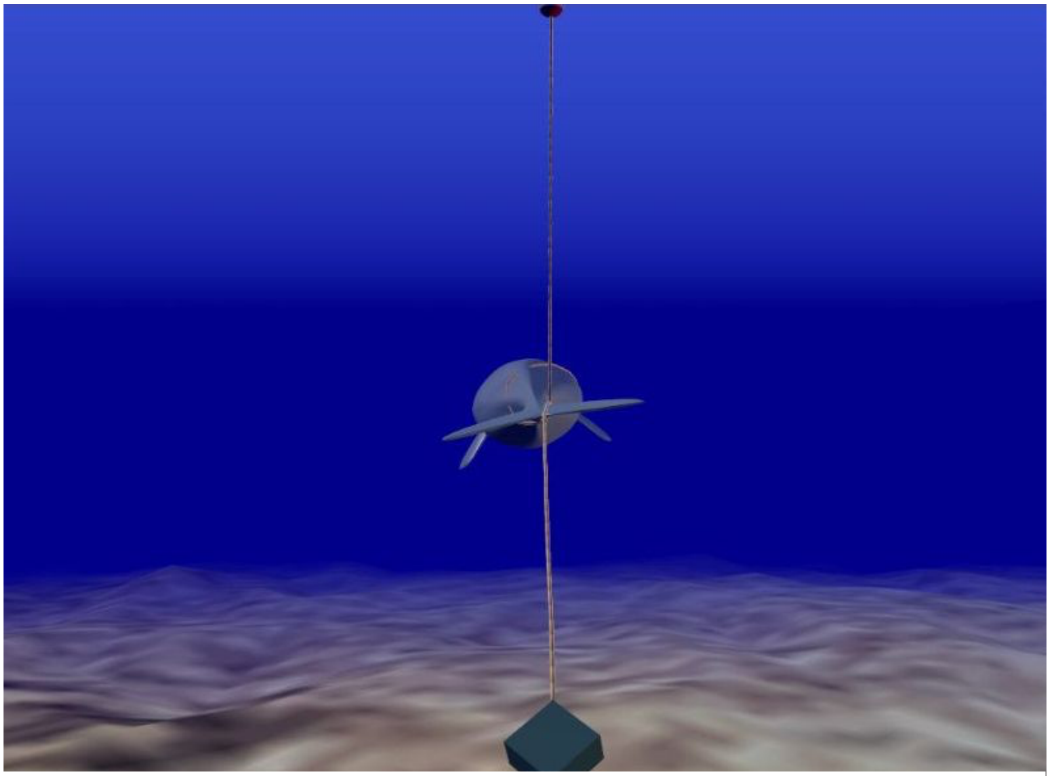


Figure 3-2. Dynamic rope model shown attached to a trap under the combined influences of current, buoyancy, and contact with a NARW.

Whale movement, particularly at the moment of initial entanglement, is likely an important factor in understanding the entanglement mechanisms and severity. While observations of initial entanglements are quite rare [4], video footage of surface active groups (SAGs) is available [29]. It is possible that the same motions displayed during SAG activity would also be displayed upon initial entanglement with fishing gear. As a portion of this project, we compiled and programmed a list of basic SAG motions and have programmed these into our VWES.

There is currently at least one model of whale articulation for a swimming NARW [30]. However, this model is restricted to swimming motions only and does not include other motions such as those observed during SAG activity or pectoral flipper movement. A more general, computationally expedient and interactive whale animation model was created for our VWES. Modern computer games create character animation by considering a bone mesh and a skin mesh [31]. Each vertex in the skin mesh is connected to up to four bones in the bone mesh with weights assigned to the connection between the skin mesh vertex and each bone according to the desired influence of that bone on the skin vertex position [32]. The computer program creates model animation by specifying the positions of the bone mesh relative to a “root” bone. Then, the skin mesh deforms as a function of the bone mesh position and the local skin mesh vertex weighting. Model animation by this method allows for arbitrary model motion according to user input and does not rely on a set of pre-scripted animations. This type of model animation is likely to be the most useful for studying whale entanglement events as it will allow the user to create various motions and test the influence of those motions on entanglement severity and probability. This type of model animation is highly computationally expedient because the model is loaded once onto the video graphics card. Then the model animation calculations take place on the massively parallel graphics card hardware (GPU computing) rather than on the CPU.

Fast and accurate calculation of collision mechanics, particularly the calculation of collisions between a trap rope and a whale fluke or flipper, turned out to be the single most effort-consuming task of this project. When a whale flipper or fluke encountered a model rope, the control spheres on the rope could tunnel through the whale surface, producing inaccurate results. In order to mitigate this tunneling problem, we employed dynamic collision detection in the program.

The static collision detection between two objects, for example, a triangle and a sphere is a relatively straightforward calculation [33]. However, for large collections of objects, the calculation can be computationally expensive. With our high-resolution model of the NARW, we had approximately 14,000 triangles making up its outer mesh. The rope model typically consisted of more than 500 control spheres or cylinders. In order to reduce the calculation effort, we used a number of hierarchical searches so that each rope control sphere would not need to be tested against each surface triangle. The hierarchical search first tested for collision between the rope control spheres and a sphere completely bounding the whale. Only those rope control points found to be within the whale’s bounding sphere were then retained for further collision calculations. Next, we tested for collision between the rope control spheres retained from the previous step and a number of local bounding regions containing a subset of the whale’s surface triangles. Finally, only the rope control spheres found to be within the local bounding regions were tested for collision using the more computationally expensive test between a sphere and a triangle. Using this hierarchical method significantly reduced the computational effort of collision detection and allowed the simulation to run in real-time.

A collision detection problem can occur when there was rapid relative motion between the whale and rope. In this case, during a single time step, we can have situations in which a rope control sphere moves completely from one side of a whale surface triangle to the other in a single time step. Thus, the collision detection algorithm would not register a collision event between the sphere and triangle. In order to mitigate this problem we use dynamic collision detection techniques [33]. In dynamic collision detection, an object is assumed to propagate along its current trajectory during the current time step. If there is a second object in the path of the first object, and if the two objects will collide at any time during the current time step, then a collision event is registered. This prevents a fast-moving object from moving completely through a second object during a single time step, thus dealing with the tunneling problem. We implemented this dynamic collision detection in the VWES.

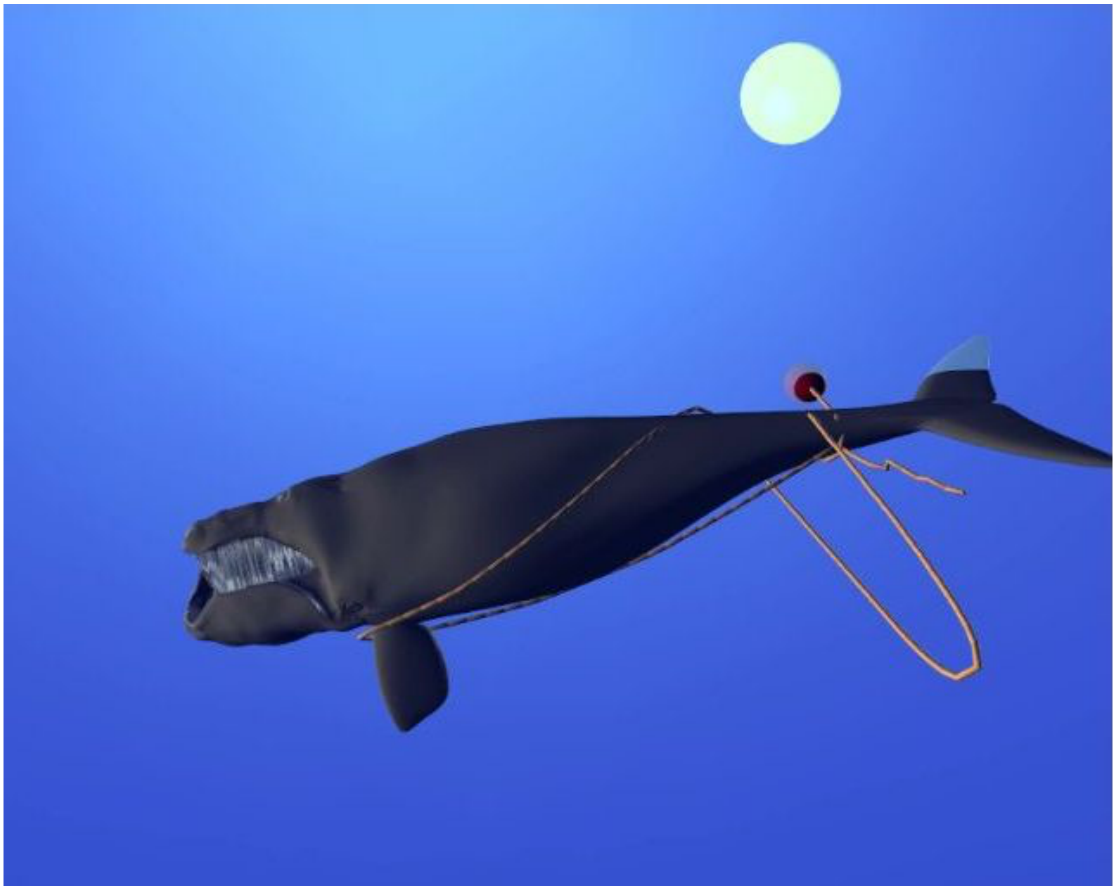


Figure 3-3. Dead, floating NARW showing flipper and peduncle wraps.

As we mentioned in the introduction section of this report, the primary goal of developing our VWES is to give marine mammal scientists a tool that can be used in an attempt to reverse engineer whale entanglement events. In Figure 3-3-3, we show a screen-capture of the VWES graphical display window. This figure shows a NARW with flipper and multiple body wraps. In this particular simulation the rope tension exceeded the breaking strength of the weak link so the trap broke free. These particular entanglements, that is, pectoral flipper wraps, and wraps around the caudal peduncle are entanglement types that are frequently observed with this whale species [2]. This entanglement scenario was generated by the VWES user in an effort to understand what motions the whale must have generated in order to become so entangled. Thus, we feel that our VWES has the potential to become a useful tool for marine mammal scientists studying the problem of whale entanglement.

Whale Articulation

We originally proposed to purchase and use Autodesk's Maya software for generating whale articulation motions. These motions would then be imported into our VWES system. Instead, we found that the Blender open-source software package allowed us to accomplish the same objectives. Therefore, we chose to use Blender rather than Maya. The Blender software system was used to build the articulated whale model and program it with a catalog of known whale motions. In Figure 3-4, we show the bone armature used for our computer animation. Computer animation of the model articulation is accomplished by programming the motion of the bone Armature rather than programming the time-dependent motion of the skin mesh. The animation of the skin mesh is accomplished by suitably weighting the movement of the skin mesh to as many as four bones per skin vertex.

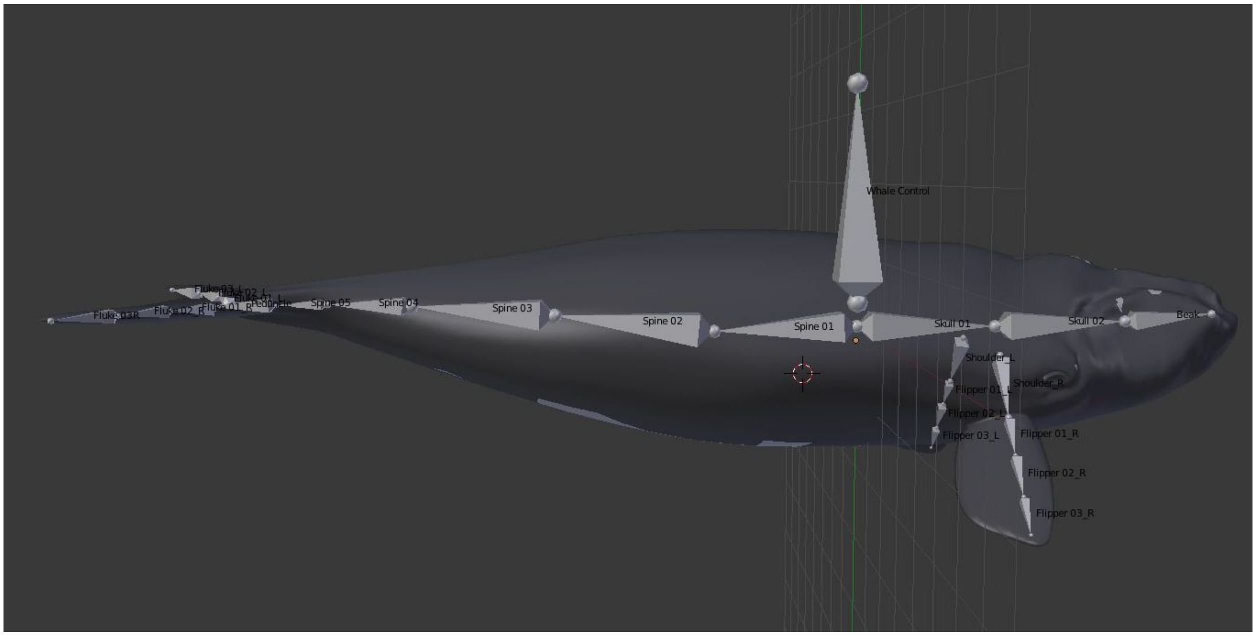


Figure 3-4. Armature (virtual skeleton) used for whale articulation. The armature consists of a single control bone (the vertical dorsal bone) for model placement in 3D space, multiple deform bones (shown) and inverse kinetics bones (not shown). As the deform-bones move, the skin mesh deforms according to mathematical weighting from nearby deform-bones.

In Figure 3-5, we show two still images of the basic swimming motion of a NARW. The left-hand frame, image (a), shows the whale near the top of its upstroke just before beginning the downstroke whereas the right hand frame, image (b), shows the whale at the bottom of its downstroke. A complete swimming cycle is generated by producing a small number of keyframes. Each keyframe contains the desired shape of the whale at that point in the swimming cycle. The computer then generates smooth motion by interpolating between the keyframes.

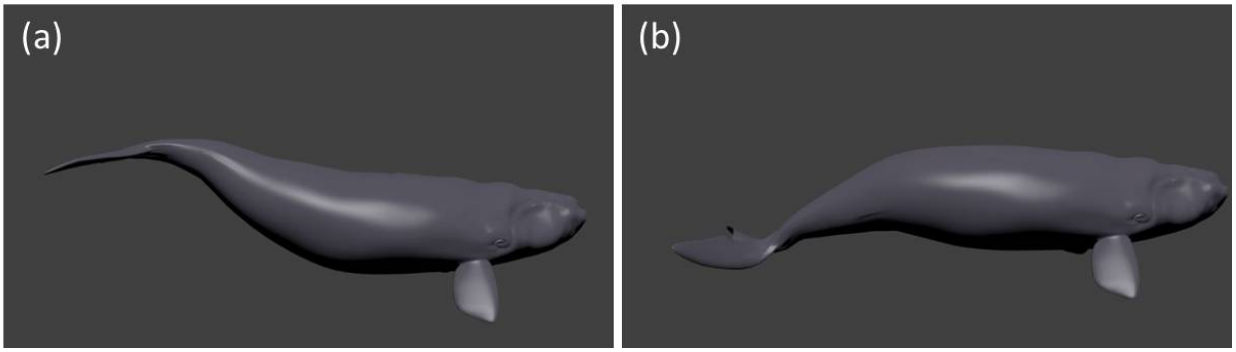


Figure 3-5. Images showing swimming motions (a) near the top of the upstroke before starting the down stroke, (b) at the bottom of the down stroke.

Since the pectoral flipper is one of the critical entanglement locations on the NARW, we also spent a considerable amount of time programming the articulation of the flippers. This flipper articulation is shown in Figure 3-6. The frames in this figure show abduction (a), adduction (b), pronation (c), and supination (d). Programming these flipper motions will allow marine mammal scientists to interrogate whether flipper motions required for maneuvering exacerbate entanglement severity.

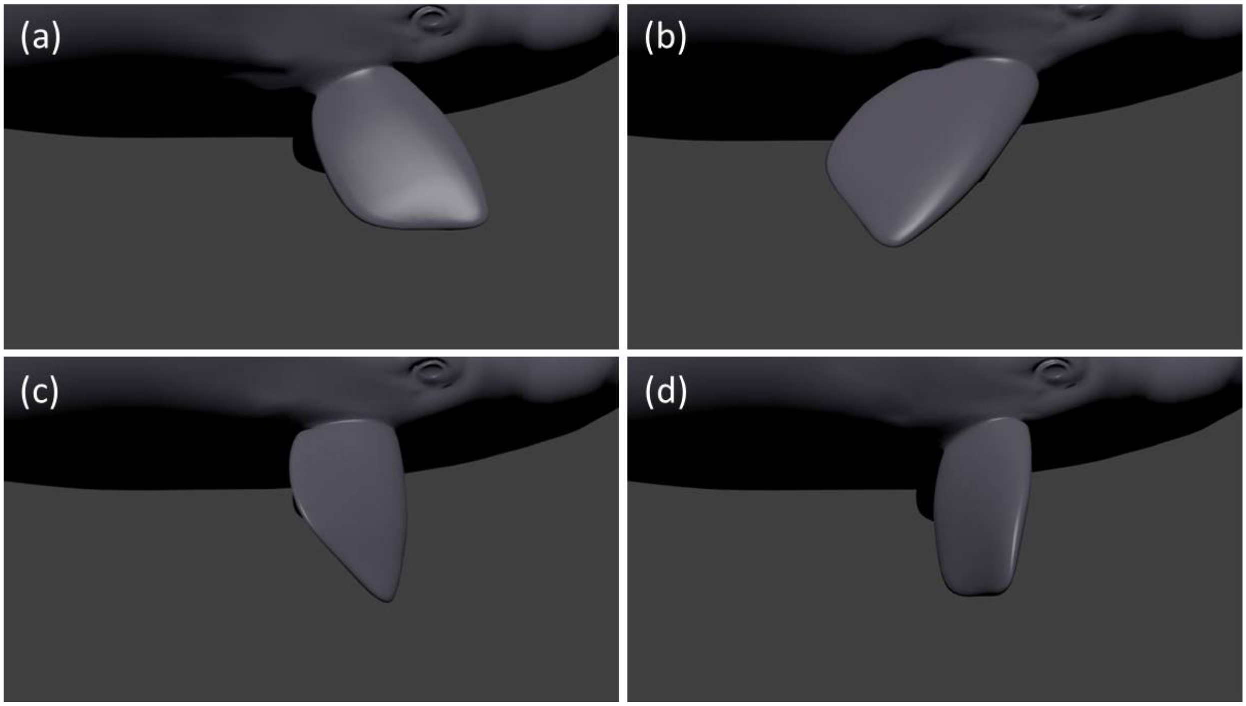


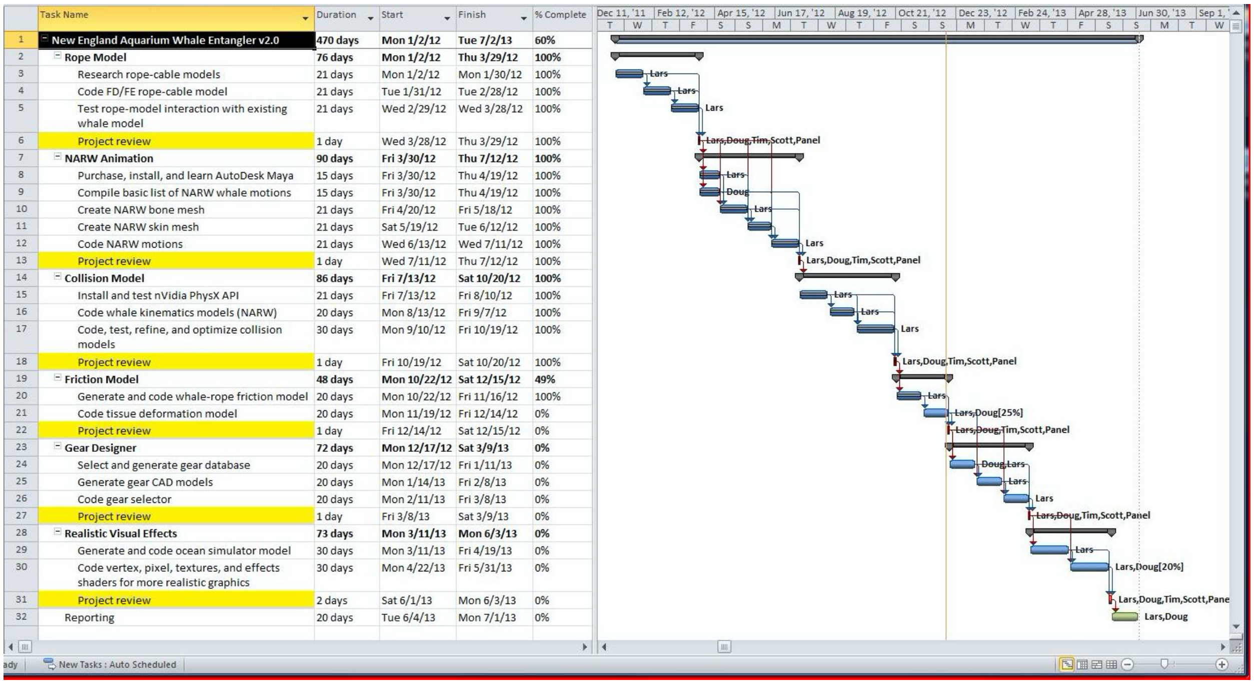
Figure 3-6. Images showing the range of flipper motions, including: (a) abduction, (b) adduction, (c) pronation, (d) supination.

Project Timeline

The original project timeline, updated for the current state of the project, is shown in Figure 3-7. Note that tasks 3, 4, 5, 8, 10, 11, 12, 15, 16, 17, and 20 are 100% complete. Major task groups (2) <u>Rope Model,</u>

(7) NARW Animation, (14) Collision Model, are 100% complete. Major task group (19) Friction Model, is 49% complete. Therefore, the entire project remains on schedule and is 60% complete.

One of the goals of this project is to determine the gear types that pose the greatest risk to NARWs of entanglement. In order to accomplish this task we must first accomplish the major task group (23) Gear Designer, which consists of three subtasks (24) select and generate gear database, (25) generate gear CAD models, and (26) code gear selector. Please note from Figure 3-7 that this major task group is not scheduled to be completed until 11 February, 2013, using separate funding. Therefore, we have not yet completed this importance study of determining which gear types pose the greatest risk of entanglement.



	Task Name	Duration	Start	Finish	% Complete
1	**New England Aquarium Whale Entangler v2.0**	**470 days**	**Mon 1/2/12**	**Tue 7/2/13**	**60%**
2	**Rope Model**	**76 days**	**Mon 1/2/12**	**Thu 3/29/12**	**100%**
3	Research rope-cable models	21 days	Mon 1/2/12	Mon 1/30/12	100%
4	Code FD/FE rope-cable model	21 days	Tue 1/31/12	Tue 2/28/12	100%
5	Test rope-model interaction with existing whale model	21 days	Wed 2/29/12	Wed 3/28/12	100%
6	Project review	1 day	Wed 3/28/12	Thu 3/29/12	100%
7	**NARW Animation**	**90 days**	**Fri 3/30/12**	**Thu 7/12/12**	**100%**
8	Purchase, install, and learn AutoDesk Maya	15 days	Fri 3/30/12	Thu 4/19/12	100%
9	Compile basic list of NARW whale motions	15 days	Fri 3/30/12	Thu 4/19/12	100%
10	Create NARW bone mesh	21 days	Fri 4/20/12	Fri 5/18/12	100%
11	Create NARW skin mesh	21 days	Sat 5/19/12	Tue 6/12/12	100%
12	Code NARW motions	21 days	Wed 6/13/12	Wed 7/11/12	100%
13	Project review	1 day	Wed 7/11/12	Thu 7/12/12	100%
14	**Collision Model**	**86 days**	**Fri 7/13/12**	**Sat 10/20/12**	**100%**
15	Install and test nVidia PhysX API	21 days	Fri 7/13/12	Fri 8/10/12	100%
16	Code whale kinematics models (NARW)	20 days	Mon 8/13/12	Fri 9/7/12	100%
17	Code, test, refine, and optimize collision models	30 days	Mon 9/10/12	Fri 10/19/12	100%
18	Project review	1 day	Fri 10/19/12	Sat 10/20/12	100%
19	**Friction Model**	**48 days**	**Mon 10/22/12**	**Sat 12/15/12**	**49%**
20	Generate and code whale-rope friction model	20 days	Mon 10/22/12	Fri 11/16/12	100%
21	Code tissue deformation model	20 days	Mon 11/19/12	Fri 12/14/12	0%
22	Project review	1 day	Fri 12/14/12	Sat 12/15/12	0%
23	**Gear Designer**	**72 days**	**Mon 12/17/12**	**Sat 3/9/13**	**0%**
24	Select and generate gear database	20 days	Mon 12/17/12	Fri 1/11/13	0%
25	Generate gear CAD models	20 days	Mon 1/14/13	Fri 2/8/13	0%
26	Code gear selector	20 days	Mon 2/11/13	Fri 3/8/13	0%
27	Project review	1 day	Fri 3/8/13	Sat 3/9/13	0%
28	**Realistic Visual Effects**	**73 days**	**Mon 3/11/13**	**Mon 6/3/13**	**0%**
29	Generate and code ocean simulator model	30 days	Mon 3/11/13	Fri 4/19/13	0%
30	Code vertex, pixel, textures, and effects shaders for more realistic graphics	30 days	Mon 4/22/13	Fri 5/31/13	0%
31	Project review	2 days	Sat 6/1/13	Mon 6/3/13	0%
32	Reporting	20 days	Tue 6/4/13	Mon 7/1/13	0%

Figure 3-7. Our current progress (as of 12/14/2012) on the WVES project Gantt chart shows us in schedule. Tasks 3, 4, 5, 8, 10, 11, 12, 15, 16, 17, and 20 are 100% complete.

Case Studies

In this section, we investigate three entanglements reported at a recent reverse entanglement workshop held at Woods Hole Oceanographic Institution. The first case study is NMFS E7-99 which is a typical mouth wrap. This whale (Eg 2753) is a female born in 1997, was entangled between 1 and 289 days, was disentangled on 05 June, 1999, and was last sighted in 2009. This whale had two prior entanglement interactions. A drawing of this entanglement is shown in Figure 3-8.

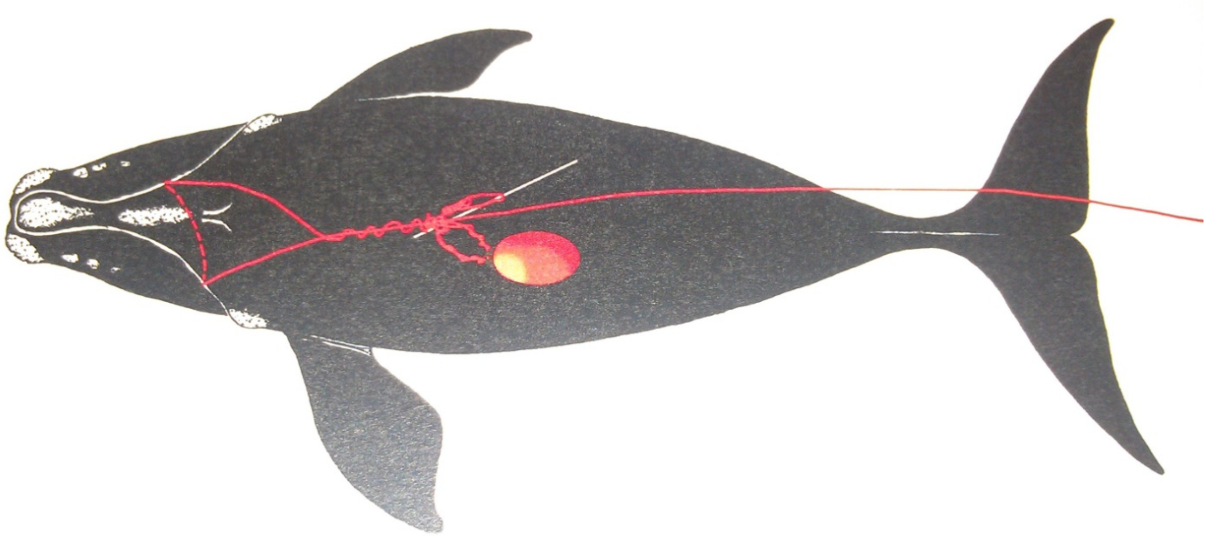
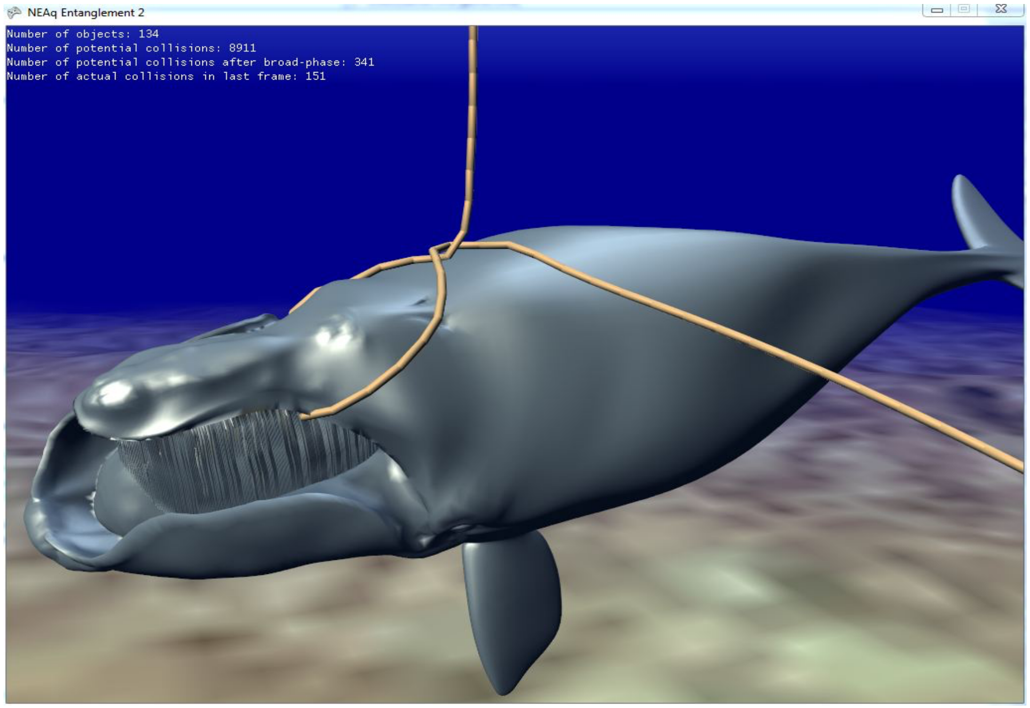


Figure 3-8. NARW entanglement NMFS E7-99. This entanglement is a typical mouth wrap.

In re-creating this entanglement using our VWES, we found that this entanglement type is most easily generated when there is a horizontal line section in the water column. Horizontal line sections can occur at slack tide when a marker line has a sinking line portion attached to the buoy and a floating line portion attached to the trap. On the other hand, when the tide is running, the trap lines tend to be taught and do not have the horizontal portion. In this case, mouth wraps are most easily generated when the whale is foraging in a sideways orientation. We show a re-creation of this entanglement type in Figure 3-9. In this re-creation, the rope becomes entangled in the baleen at first encounter. Subsequent whale motions after first encounter cause the rope to become tangled.

Although our current whale models only include open mouth and closed mouth configurations, we would like to create an additional whale model that allows the whale to open and close its mouth. Our hypothesis is that when a whale first encounters a rope while foraging, it closes its mouth, which then drives the rope up into the baleen plates were the rope becomes firmly wedged. Thus, adding mouth articulation will be an important feature to add to our VWES.



```
Number of objects: 134
Number of potential collisions: 8911
Number of potential collisions after broad-phase: 341
Number of actual collisions in last frame: 151
```

Figure 3-9. Mouth wrap re-created with the VWES. The entanglement of the rope in the baleen occurs on first encounter. The subsequent rope twisting results from the whale's movements after the first encounter.

The next case study we consider is a typical flipper wrap. This entanglement (NMFS E25-05) involved a female NARW (Eg 3445) born in 2004. The whale was entangled between 9 and 296 days. The line wrapped the body near the area of the flippers and was twisted under the whale’s ventral side and trailed 400ft aft. The gear included 3/8 polypropylene vertical line, 5/17 and 7/16 polysteel vertical lines and included three hard buoys. This whale was partially disentangled on 13 December, 2005 and was last sighted in 2006. An image of the entanglement is shown in Figure 3-10.

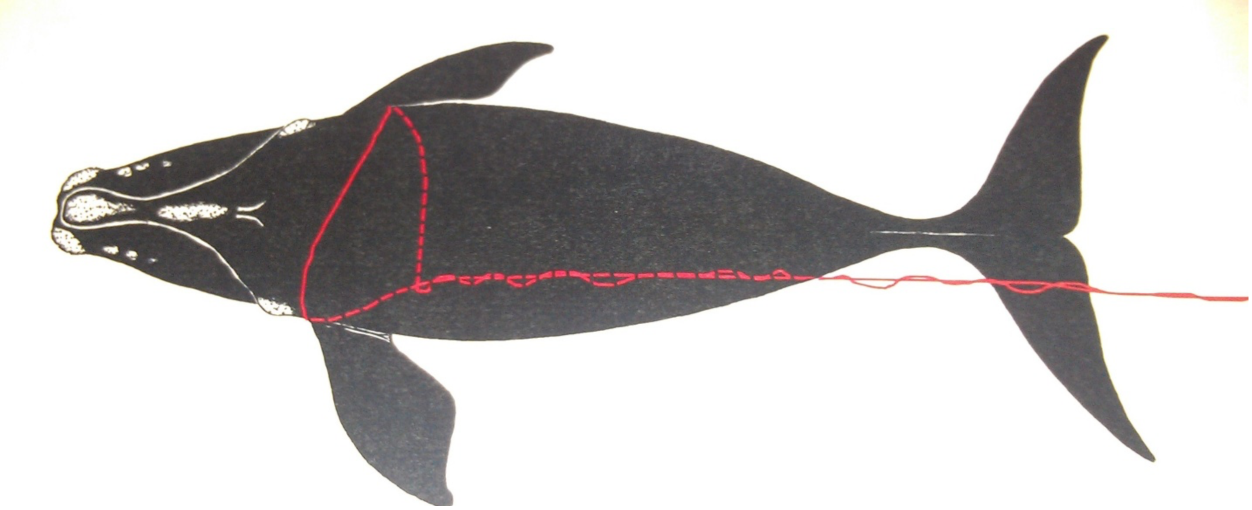
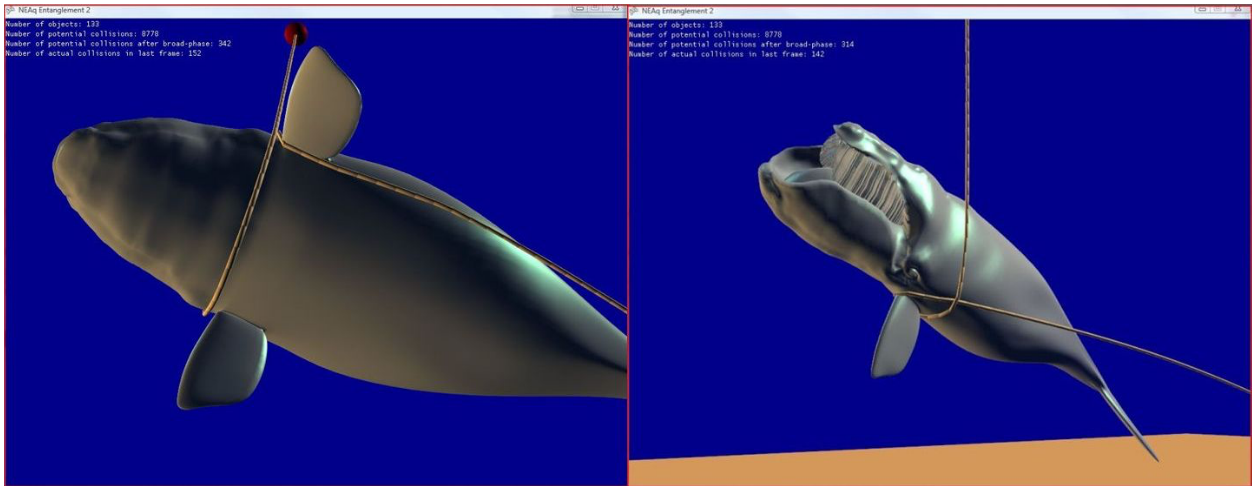


Figure 3-10. NARW entanglement E25-05. This image shows a wrap involving a flipper, one of the common locations for entanglement initiation.



```
Number of objects: 133
Number of potential collisions: 8778
Number of potential collisions after broad-phase: 342
Number of actual collisions in last frame: 152
```

```
Number of objects: 133
Number of potential collisions: 8778
Number of potential collisions after broad-phase: 314
Number of actual collisions in last frame: 142
```

Figure 3-11. Flipper-initiated entanglements generated with the VWES. The left image shows the results of an initial encounter with the left flipper followed by a roll. This results in a flipper and body wrap. The right image shows the result of an initial flipper encounter followed by flipper “thrashing”.

Figure 3-11 shows two different re-created flipper wraps. The left image shows the result of a first encounter at the leading edge of the left flipper followed by a roll. The role created the body wrap after first encounter. The right image shows how trap line can become circumferentially wrapped around the flipper. We generated this entanglement by a first encounter at the leading edge of the flipper followed by flipper thrashing motions.

In re-creating various flipper wraps several observations can be reported. First, the roll direction matters after first encounter. For example, if the whale strikes a trap line with the flipper and rolls toward the line, we found it easier to create a body wrap. Additionally, swimming up or down current was also important. For the whale swimming down current the line remains in tension after the first encounter. On the other hand, for the whale swimming up current, the line can become slack as the whale drags the line against the current. In this case, the slack line has a greater probability of wrapping the whale. An additional observation is that flipper motion at first encounter is likely very important in the entanglement. For example, if the whale is swimming with the flippers swept aft, as would be common in cruising, and then it encounters a line, it will sweep its flippers forward in order to use these control surfaces to turn away from the line. With the flippers swept forward it was easier for us to generate entanglements since the rope was not shed from the flipper is easily.

The final entanglement case study that we report here involves another common entanglement type; the wrap at the caudal peduncle. In Figure 3-12, we show a typical peduncle wrap. This entanglement (NMFS E15-02) involved a female NARW born in 2001 (Eg 3107) that had been entangled between 57 and 226 days. This whale was disentangled on 01 September, 2002 and was dead on 13 October 2002. This whale had one prior entanglement interaction.

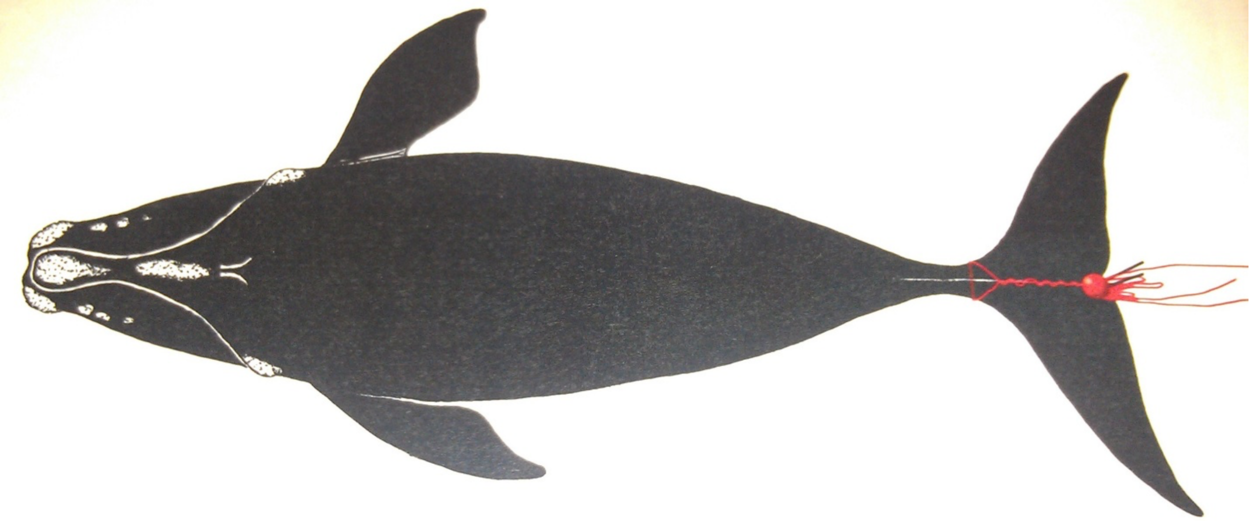
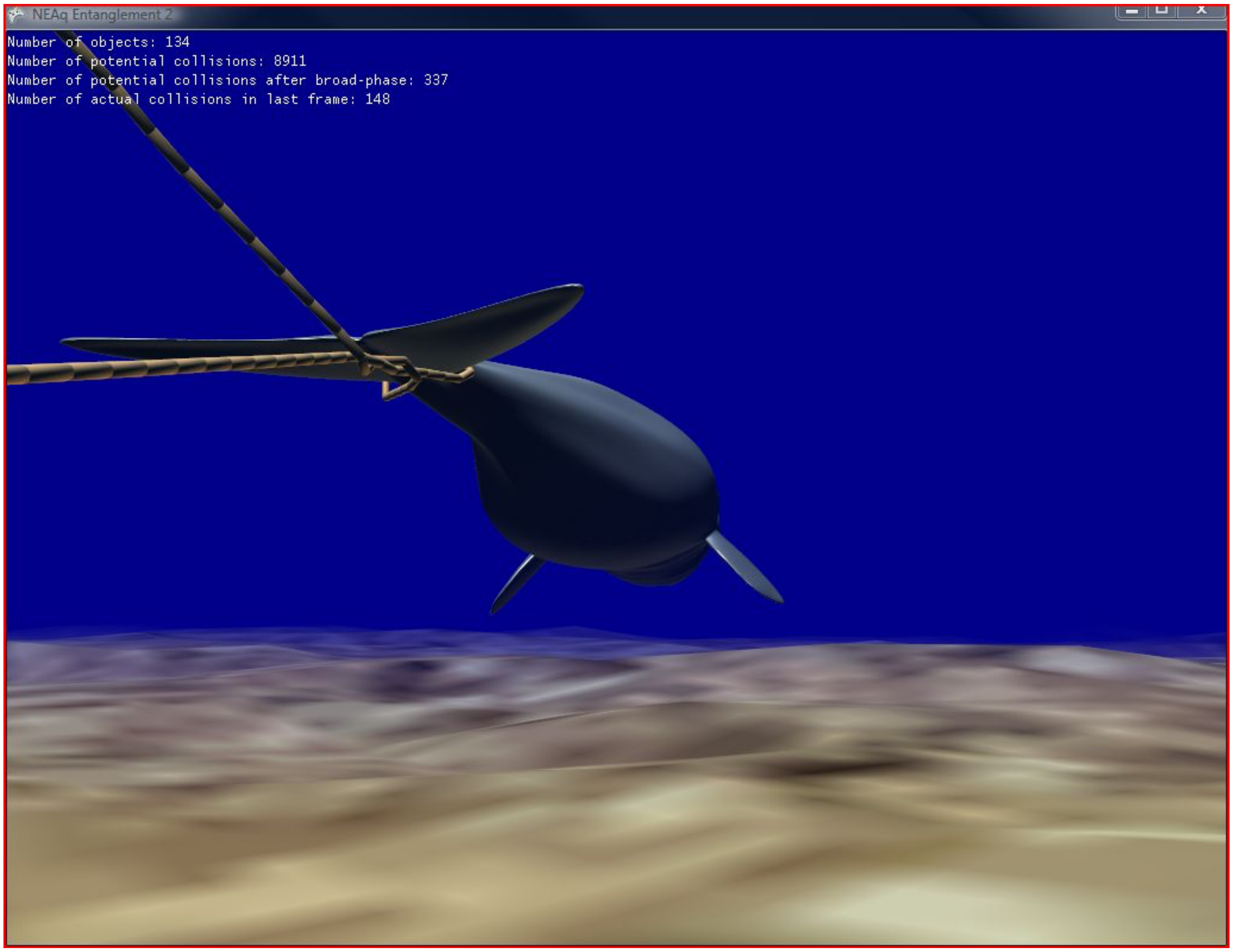


Figure 3-12. NARW entanglement E15-02. This case study shows a typical caudal peduncle wrap.

A re-creation of this entanglement type is shown in Figure 3-13. We found that we could re-create this entanglement type most reliably with a vertical trap line. That is, with a line under tension as it would be when the tide is running. To generate this entanglement type, we swam the whale toward the rope. Then, just before striking the line, we turned the whale using a roll maneuver to avoid the rope. After the roll maneuver, the trailing edge of the tail is nearly vertical. Following this, as the whale swims past the rope, it strikes the line near the peduncle region. If there is sufficient amplitude left in the tail stroke, then the line can strike the peduncle and move to the opposite side of the flukes on either side of the peduncle. As the whale continues to swim, the line becomes tightly wrapped around the peduncle. The twist in the line shown in the re-creation was created by having the whale execute a barrel roll maneuver after wrapping the peduncle.



```
Number of objects: 134
Number of potential collisions: 8911
Number of potential collisions after broad-phase: 337
Number of actual collisions in last frame: 148
```

Figure 3-13. Peduncle wrap re-created with the VEWS.

Conclusion

In developing our VWES, one area of the project that consumed a large amount of effort was dynamic collision detection between the whale and the trap line. Collision between a segment of the trap line and a thin whale feature, such as the pectoral flipper leading/trailing edge or tail fluke leading/trailing edge, was the most problematic collision detection problem. Additionally, accurate simulation of rope dynamics under varying loading including tension from the buoy and trap, friction with the animal, drag, and buoyancy were also areas where we had to devote substantial efforts.

Although still under development, the virtual whale entanglement simulator developed under this project will assist marine mammal scientists, fisheries experts, fishing gear designers, and bycatch reduction scientists in understanding what gear types and what whale behaviors lead to entanglements. Additionally, through the virtual testing of different - perhaps new or untested - gear types, this VWES will help to identify promising new gear techniques to avoid baleen whale entanglements.

Acknowledgments

We would like to thank Dr. Anna E. Nousek McGregor for providing the whale model and models of some of the fishing gear used in this study. This investigation is supported by the Consortium for Bycatch Reduction, by the U.S. DOC-NOAA Grant# NA09NMF4520413 and by the New England Aquarium.

References

1. Kraus, S.D., et al., *North Atlantic Right Whale in Crisis.* Science, 2005. **309**(5734): p. 561-562.
2. Cassoff, R.M., et al., *Lethal entanglement in baleen whales.* Dis Aquat Organ, 2011. **96**(3): p. 175-85.
3. Knowlton, A.R., et al., *Analysis of Scarring on North Atlantic Right Whales (Eubalaena glacialis): Monitoring Rates of Entanglement Interaction: 1980-2002.*, N.M. Fisheries, Editor 2005.
4. Wienrich, M., *Behavior of a Humpback Whale (Megaptera novaeangliae) upon Entanglement in a Gill Net.* Marine Mammal Science, 1999. **15**(2): p. 559-563.
5. McGregor, A.E.N., *The Cost of Locomotion in North Atlantic Right Whales (Eubalaena glacialis).* in *Marine Science and Conservation*2010, Duke University: Durham, NC. p. 158.
6. Pettis, H.M., et al., *Visual health assessment of North Atlantic right whales (Eubalaena glacialis) using photographs.* Can. J. Zool., 2004. **82**(1): p. 8-19.
7. Brillant, S.W. and E.A. Trippel, *Elevations of Lobster Fishery Groundlines in Relation to Their Potential to Entangle Endangered North Atlantic Right Whales in the Bay of Fundy, Canada.* ICES Journal of Marine Science, 2009. **67**(2): p. 355-364.
8. Anon, *Comparison of OpenGL and Direct3D.* , ed. F.P. Miller, A.F. Vandome, and J. McBrewster. 2009: Alphascript Publishing.
9. Cawood, S. and P. McGee, *Microsoft XNA game studio creator's guide*. 2nd ed. 2009, New York: McGraw-Hill.
10. Miles, R., *Microsoft XNA Game Studio 4.0 : learn programming now!* 2011, Redmond, WA: Microsoft Press.
11. Miller, T. and D. Johnson, *XNA Game Studio 4.0 Programming. Developing for Windows Phone 7 and Xbox 360.* 2011, Boston: Addison Wesley.
12. Reed, A., *Learning XNA 4.0*. 2011, Sebastopol, CA: O'Reilly.
13. Jaegers, K., *XNA 4.0 Game Development by Example: Beginner's Guide*. 2010, Birmingham: PACKT publishing.
14. Harbour, J.S., *XNA Game Studio 4.0 for Xbox 360 Developers*. 2012, Boston: Cengage Learning.
15. *DigitalRune Engine: 3D Game Engine for .NET and XNA*, in *Ternberg* 2011.
16. Anon. *Computer physics engines, including: Collision Detection, Particle System, Pynamical simulation, Rag Doll Physics, Havok (software), Physics Engine, Physics Processing Unit, Open Dynamics Engine, Endirphin (software), PhysX, Game Physics, Unique, CUDA.* . 2011: Hephaestus Books.
17. *nVidia PhysX SDK 2.8.1*, 2011 San Fancisco.
18. McKenna, H.A., J.W.S. Hearle, and N. O'Hear, *Handbook of fibre rope technology*. 2004, Boca Raton: CRC Press.

19. Tsukrov, I., et al., *Numerical modeling of nonlinear elastic components of mooring systems.* IEEE Journal of Ocean Engineering, 2005. **30**(1): p. 37-46.
20. Tahar, A. and M.H. Kim, *Coupled-dynamic analysis of floating structures with polyester mooring lines.* Ocean Engineering, 2008. **35**: p. 1676-1685.
21. Costello, G.A., *Theory of wire rope*. Second ed. 1997, New york: Springer.
22. Imrak, C.E. and C. Erdonmez, *On the problem of wire rope model generation with axial loading.* Mathematical and Computational Applications, 2010. **15**(2): p. 259-268.
23. Fridman, A.L., *Calculations for Fishing Gear Designs*. 2008, LaVergne: Pierides Press.
24. Brillant, S.W. and E.A. Trippel, *Elevations of lobster fishery groundlines in relation to their potential to entangle endangered North Atlantic right whales in the Bay of Fundy, Canada.* ICES Journal of Marine Science, 2010. **67**: p. 355-364.
25. Flory, J.F., et al., *Computer model to predict long-term performance of fiber rope mooring lines*, in *Offshore Technology Conference*2005: Houstan, TX, USA.
26. Lee, C.-W., et al., *Physical modeling of underwater flexible systems dynamic simulation.* Ocean Engineering, 2005. **32**: p. 331-347.
27. Servin, M., et al., *Hybrid, Multiresolution Wires with Massless Frictional Contacts.* Ieee Transactions on Visualization and Computer Graphics, 2011. **17**(7): p. 970-982.
28. Imanishi, E., T. Nanjo, and T. Kobayashi, *Dynamic simulation of wire rope with contact.* Journal of Mechanical Science and Technology, 2009. **23**: p. 1083-1088.
29. Kraus, S., *Video footage of North Atlantic right whale surface active groups (SAGS)*, 2010: Boston.
30. Duffy, A., et al., *Numerical animation of a North Atlantic right whale.* Preprint, 2009.
31. Erleben, K., et al., *Physics Based Animation*. 2005, Hingham: Charles River Media, Inc.
32. Parent, R., *Computer Animation Algorithms & Techniques*. Second ed. 2008, Burlington: Morgan Kaufman.
33. Ericson, C., *Real Time Collision Detection.* 2005, Amsterdam: Morgan Kaufmann Publishers.