How to Design and Build a Radio-Controlled Working Cargo Ship Model for the High School Engineering Challenge

R.Farley 5-2002

Table of Contents

Propeller-motor-hull speed performance predictions
- Power Required
- Power Available

Practical ship design
- Bow shapes
- Stern shapes
- Rudder types
- Keels
- Propeller placement

Practical ship building
- Construction materials
- Layout tools and methods
- Construction methods
- Propeller installation (stuffing box, prop shaft, u-joint)
- Motor installation (cheater plate)
- Rudder installation
- Deck house
- Paint and finish
- Making the cargo containers
- Batteries
- Wiring
- Radio control installation
- TESTING! TESTING! TESTING!

Operating the ship
- Transportation and safe display of the ship model
- Radio control protocols
- Stacking the cargo
- Driving the course

Writing a technical report

Making drawings

Chapter 1 Cargo Ship Engineering Challenge

General considerations

The Baltimore Museum of Industry has for several years now hosted an engineering competition for high school-aged students whereby a small team of students (8 or less) must scratch-build a radio-controlled model cargo ship, with the aid of a 'mentor'. This ship must carry pine blocks for cargo around a buoyed watercourse approximately 200ft (60m) in the inner harbor next to the waterfront museum. There are constraints on the size of the model ship, but generally they are about 4.5ft (1.4m) long, and with cargo can weigh over 100lbs. The teams are given the 12volt electric motors (which suspiciously look like old windshield wiper motors from a car), and are given the choice of 1 or 2 electric motors. The more electric motors you use, the more you are penalized, yet it might make you go faster, but two motors would drain the batteries quicker and there would be less cargo space…. Questions like these arise constantly during the design phase, and you are encouraged to ask questions and try to have them answered one way or another (ask advice, research books, do the math, do a test, etc…). There is a performance formula given to measure the efficiency of your ship, how many dollars per pine block cargo container per foot of distance transported. It consists of a 'fixed cost' and an 'operating cost'. The fixed cost is supposed to represent the cost of constructing a real ship (buying one for ~$100 million), the bigger the more expensive. The operating cost represents the expense of operating your new ship; paychecks for the crew, insurance, docking, maintenance and repair, fuel for the engines. The more cargo you can move fast, the operating costs are more spread out and therefore cheaper per cargo container. The two different kinds of costs are, of course, at odds with each other. The fixed costs want you to be small, and the operating costs want you to be big, fast, but few motors. This allows for optimization within the constraints of the rules. The basic rules regarding the configuration are that the length + the beam (width) must be less than or equal to 66 inches. The draft (depth of the hull below the waterline) must be less than or equal to 5 inches. The length to beam ratio must be between 3 and 6. Within these constraints, an optimized design can be calculated (it looks impossible now, but just keep reading…).

Official Rules (condensed somewhat, but basically verbatim)

CHALLENGE PROBLEM:

Design, develop, build, and demonstrate a radio-controlled scale model of a ship intended to economically carry containerized cargo over an ocean route. The model will be required to demonstrate its cargo capacity and fully loaded performance by carrying scale containers over a course in the inner harbor.

The competition involves five main components, a written report submitted two weeks prior to the actual competition, an oral report on the day of the competition, the actual design and construction of the entry, the reliability of the entry, and the demonstrated performance.

WRITTEN REPORT AND DRAWINGS *Competition value: 15 points*

This report should present and explain all facets of the design, and the rationale for selecting specific design parameters and selecting/rejecting individual features. For example, why was the overall length, waterline, length, beam, draft, sail plan and hull shape chosen? What alternative designs were rejected, and why? What testing was performed, and what were the results?

ORAL REPORT *Competition value: 10 points*

This is a 10-minute presentation by one of the members of the group, summarizing the contents of the written report. It will be followed by 5 minutes of questions from the judges.

DESIGN AND FABRICATION *Competition value: 35 points*

Any mono-hull design is acceptable, and the hull may be constructed of any rigid material. The boats do get banged around a bit, so ability to withstand minor collisions is a worthwhile consideration - as is the watertight integrity and cushioning of the radio receiver/battery compartment. Propulsion will be provided by one or two specified electric motors operating at no more than 12 volts (nominal). Motors for all entrants are available from Baltimore County Schools Supervisor of Technical Education. Running gear (propeller and propeller shaft and stuffing tube or other propulsor) may be purchased from any source. A standard multi-channel radio control unit functioning in the R/C band must be used, capable of controlling at least engine speed, forward/ reverse, and rudder.

The model must be scaled 1"=10'0" (1:120) and conform to these basic specifications:

- ❖ The sum of the overall length (L) and beam (B) shall not exceed 660 feet (66 inches). Appendages such as rudders are <u>not</u> included in these limits, so long as they are reasonable and necessary to the proper functioning of the vessel. The ratio of length to beam must be in the range 3:1 to 6:1.
- ❖ Maximum draft of the hull itself is not to exceed 50 feet (5 inches).
- ❖ The vessel must be marked with a maximum load line that is at least 30 feet (3 inches) below the deck edge measured amidships.
- ❖ The design need not include a full deck; containers can (and for stability should) be stacked continuously up from the keel and may extend above the gunwales (upper edges of the hull), provided they are at least 1 inch below the bridge deck (after all, the bridge crew must be able to see where the ship is going!).
- ❖ The vessel must have a deckhouse that occupies at least 5% of the hull overall length. This deckhouse must extend at least 50 feet (5) inches) above the gunwales and at least 10 feet (1 inch) above the top layer of cargo. No cargo may be loaded in way of the deckhouse.
- ❖ At least 15% of the length of the hull must be free of cargo. This space may be split between the deckhouse and the forecastle and may be used for machinery and/or electronics and battery access.
- ❖ The model cargo containers which will be used are 1 inch high x 1 inch wide x 4 inches (full size) or 2 inches (half size). Just as in the real world, their weight will vary - between 1 and 3 ounces for the full size container. Single large pieces of wood representing multiple containers (i.e. the dimensions are multiples of individual container dimensions, such as 1"x12"x16" All containers must be provided by the respective teams.
- ❖ The vessel must have adequate stability when fully loaded. <u>This is important – test it before the challenge date!</u> Stability may be demonstrated by:

- Calculating metacentric height (GM) in excess of 7.5 feet (3/4 inch) by placing a one pound weight 4 inches either side of the centerline and showing no more than 3 degrees of heel, OR
- Having a roll period (left - right - back again) of less than 2 seconds.

- Vessels must be painted or marked for identification - and the quality of workmanship and finish is a factor in judging! The judges expect the model to look like a ship. Failure to adhere to these requirements will result in the loss of a significant number of points.

Each team should provide a floor stand for its ship model, high enough to permit working on its entry during the challenge (the table space available in previous years cannot be guaranteed).

RELIABILITY *Competition value: 10 points*

Reliability is the result of both design and construction. Each team will be evaluated on the reliability of their entry as observed by judges during the performance demonstration. Such factors as the number of failures, the severity (with respect to their effect on the entry's ability to complete the demonstration), and the total time to repair them, will be judged.

PERFORMANCE DEMONSTRATION *Competition value: 30 points*

Upon arrival at the competition site and after the judges' examination of their entry, each team must develop a load plan to carry as much cargo as possible without exceeding the load line, height above deck, allowable cargo space, or stability limits. Once loaded, each cargo ship will perform a timed run consisting of getting underway from a wharf, running a course around buoys, and maneuvering back alongside the wharf. The goal will be to have the minimum freight rate, which is determined by the following formula:

Freight Rate = [(Fixed Costs) + (Operating Costs)] / (Cargo Carried x Distance Traveled)
Where: Fixed Costs = Length x Width x Draft Loaded x $10 (dimensions in inches)
Operating Costs = time to run course in seconds x $10 per second x no. of propulsion motors
Cargo Carried = total number of full-sized containers (or equivalent half-sized)
Distance Traveled = length of course in feet

In evaluating the various trade-offs that must be made during the design phase, keep in mind that the course will be a few hundred feet long, and will be in the Inner Harbor and subject to whatever weather Mother Nature decides to serve up, not a swimming pool or test tank – remember the objective was to model a vessel to reliably transport cargo over a long distance in the open ocean. Maneuverability sufficient to get underway and moor within a reasonable period of time is essential, but the key is to carry the greatest number of containers the fastest.

PRIMARY RESOURCE FOR INFORMATION ABOUT THE ENGINEERING CHALLENGES

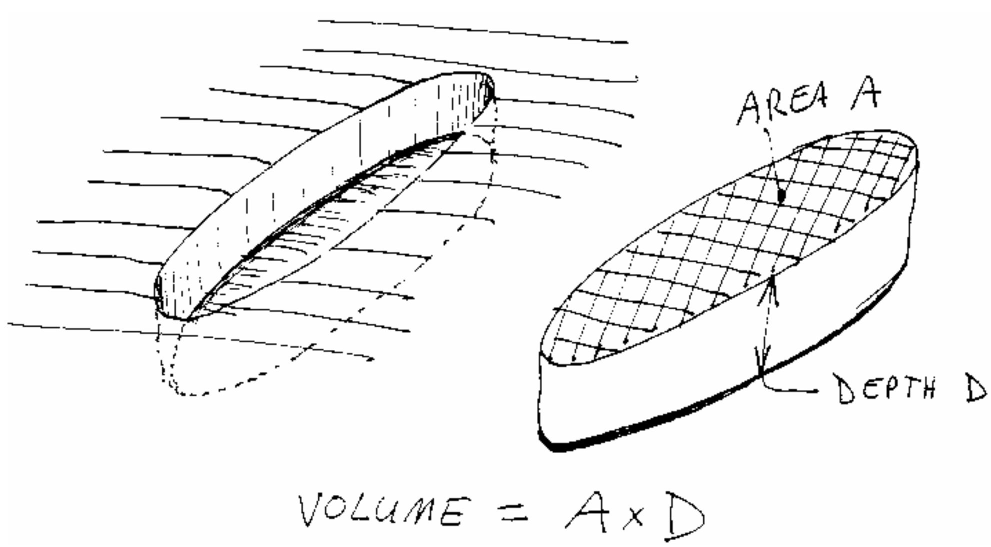
Baltimore Museum of Industry – Special Programs Department
1415 Key Highway • Baltimore, MD 21230
(410) 727-4808, Ext. 111
Fax 727-4869
www.thebmi.org

Chapter 2 General Principles

The general principles are the background material to help us understand the concepts ahead. Individually taken, they are simple principles to comprehend. Combined together, they allow for an understanding of the physical world about us, and how the principles interplay. This is not a treatise on explaining the entire universe! Just a small slice as it affects ship design (a *very* small slice…)

Length, Area, Volume

This may seem obvious, but what the heck, it gets harder farther on, so lets do something simple. Take an object like a book. You notice there are 3 lengths you could measure; the height H, the width W, and the depth D, in inches of length. If you multiply the height by the width (H x W), you'll get the area 'A' of the book's face in square inches. Check this out by drawing on paper the rectangular outline of the book's face, and drawing a grid pattern within the rectangle using 1 inch spacing. Count the number of squares within the rectangle, and it should be exactly what you calculated. Next calculate the volume 'V' in cubic inches. This is simply multiplying height H and width W and depth D (H x W x D). Simple, right? But another way to look at it is to say H x W is the cross-sectional area 'A' having a depth 'D', or V = A x D. This is powerful, as you can now take any shape with a constant cross-sectional area that you know, and determine the volume if you also know the depth. Say you've got a cylinder with a radius R and length L. The cross-sectional area A is πR^2, so the volume V = A x L, or $\pi R^2 \times L$. Lets say you have a constant cross-sectional shape that's not easy to calculate (say the sole of your shoe), but you were able to approximate by counting squares on a graph sheet of the outline shape. Call that area 'A', and the volume will now be that area times any depth you choose to make it. This is useful to ship design, as a cargo ship is basically boxy with rounded nose and tail. Imagine the ship in the water. Imagine the water freezing solid. Now imagine the ship disappearing, *poof*! A footprint of the ship's outline on the surface is visible in the ice - find the area 'A' of that footprint. Now, measure how far down in the ice it goes, it's depth 'D'. The volume of water 'V' that the ship was displacing (had the ship not been there in the first place) is: you guessed it, V = A x D! Since a real ship has a more curvaceous 3-dimensional shape, this simple equation overestimates the volume, but for a boxy cargo ship, not by much.

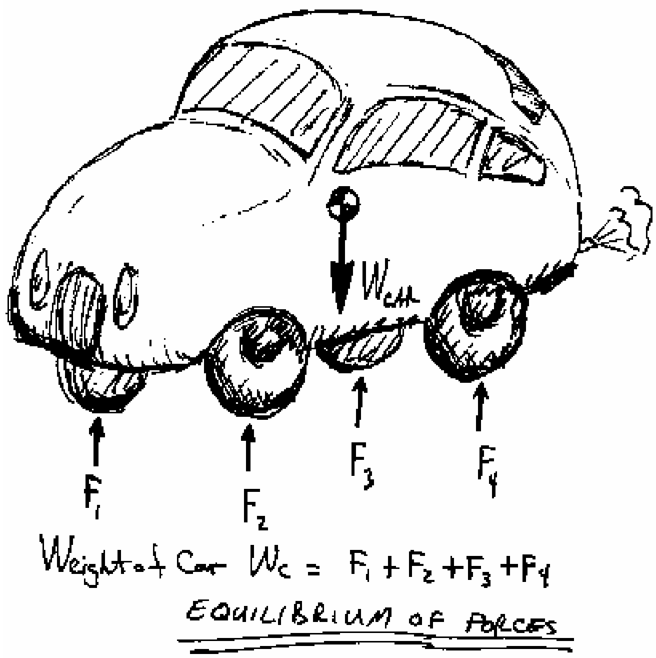


Scaling laws (squared-cubed law)

Scaling laws are used to predict the types of performance or problems that may arise when you make a device bigger or smaller than what you are accustomed to doing. What does that mean? Lets say I have a sailboat design that from years of fine tuning, trial and error, it finally works great. I suddenly get the urge to build one twice as big! Will I go twice as fast, will the boat weigh twice as much, will the thrust from the sails be twice as forceful? Scaling laws can help give an insight as to what to expect, and how you should alter the design. Let us consider weight first. If I have a block of wood, and make another block of the same material twice as big, it will weigh 8 times as much! You see, every dimension of our 3 dimensional block doubled, so twice length x twice width x twice depth = 8 times the original mass. It follows a cube law, where if 'SF' is the scale factor (2,3,4, ½, ¼ , or any number really), and the original weight (or volume) is 'W1', then the new weight $W2 = W1 \times SF^3$. The sails on the other hand follow a square law, as their thrust is proportional to their area. So the new sail area $A2 = A1 \times SF^2$. This illustrates the infamous square-cube law, which plagues the modelers of airplanes and boats. Let us say you like a sailboat design and want to make a working radio-controlled scale model of it. If you make it half scale (big model…), the boat will weigh 1/8 as much as the real McCoy, but the sails will have reduced their thrust to ¼ of the original. That's like having twice as much sail force per pound of boat as the original, and it will most likely tip over from an over-press of sail. So now you either reduce the sail area, or make the keel twice as long to handle the turn-over force. You get the picture, that scaling original designs to a different size can lead to head-scratching problems. Big sailboats can have huge sails and short keels relative to the length of the boat, and small sailboats need small sails and longer keels relative to their boat length. Scaling laws can also apply to propeller sizes, motor sizes, top speed, stability and geometrical factors.

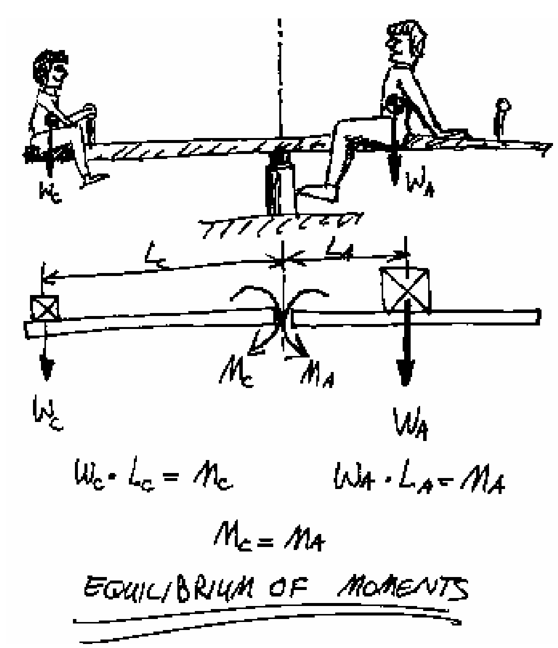
Force and equilibrium

We have all experienced force, such as gravity. The political kind, such as your older sibling making you do something, will not be discussed. Pick up something heavy, and you feel yourself staggering downward and then drop it. Grab the ends of a rubber band, stretch it and feel the force trying to snap back together, but straining your fingers you manage to hold it apart. Stand on a hilltop on a windy day and feel the force of the wind on your body as you lean into the wind for balance. Hold a garden hose with a nozzle, and pull the handle full blast. You feel a rocket-like thrusting force, but you bravely stand your ground. Lay down on the ground. Lay down on water and float. In all cases you were feeling a force, created by different mechanisms. Some by gravity, some by elastic forces, some by friction forces, and some by direct momentum transfer (rocket propulsion). Those forces were also in equilibrium. That is, a force existed, and a countering reaction force exactly equal and opposite materialized to keep the objects in question static and unmoving. Of course, you did some of that yourself. The earth under your feet must be exerting a reaction force exactly equal but opposite to your weight. If it were not in perfect equilibrium, you would either accelerate downwards or upwards. The upwards force of water on a floating boat must also be in perfect equilibrium with the downwards weight of the boat. It follows then, that the sum of all forces acting on any object at rest must be equal to zero. Want to weigh a car, but don't have a scale big enough? If you place a bathroom scale (a hefty one) under each wheel and read the weight reported by each scale, then the total weight of the car is equal to the sum of all the bathroom scale readings. The weight of the car is divided-up in some manner between 4 tires. The 4 tires have a reaction load to the car's weight such that the car is in equilibrium, so the sum of all forces on the car is zero. The weight is pushing down, so the tires must be pushing up. Each force at the 4 tires is measured by a bathroom scale. The sum of those 4 forces better equal the weight of the car in order to be in equilibrium!



Lever arms and moments (torque)

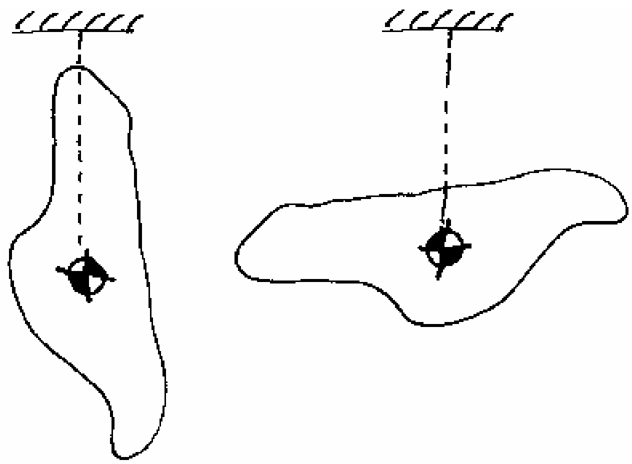
Ever pry open a can of paint with a screwdriver blade? You certainly couldn't exert that much force on the paint can lid directly by pulling up with your fingernails, but by using leverage you can magnify the force applied to open that stubborn lid. Ever see a see-saw with a child on one end and an adult sitting halfway up the board in order to balance? The lighter child has a longer lever arm (moment-arm as an engineer would say) to balance the heavier adult with the shorter moment-arm. At the hinge point, they are each creating a torque that balances the other. The torques (or moment, as an engineer would say) are of equal magnitude but opposite directions. A moment 'M' is simply the product of force 'F' and it's moment arm 'L'; M = F x L. Since the see-saw is in equilibrium, the moment produced by the child and the adult are equal, Mchild = Madult, or Fc x Lc = Fa x La. The



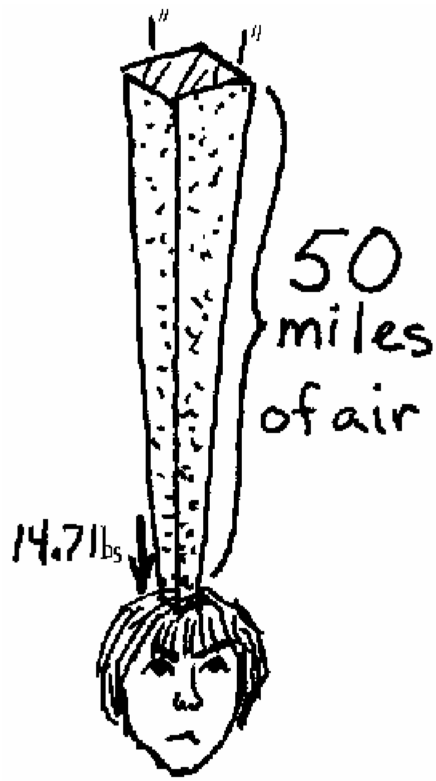
forces Fc, Fa, are equal to the weight of the child and adult respectively, and the lever arm lengths from the hinge center are Lc, and La.

Center of gravity

The center of gravity of any object is the point whereby if you could attach a string to that point (and have it magically not touch or interfere with the object), you could suspend the object in perfect balance no matter how you angled the object. It is the 3-dimensional balance point, in other words. It is the point where all the 'moments' due to gravitational attraction on each atom equal zero. That last statement may have confused the issue just when you thought you understood it, but it provides the basis for determining the center of gravity mathematically. Which we won't do here…yet.



Pressure

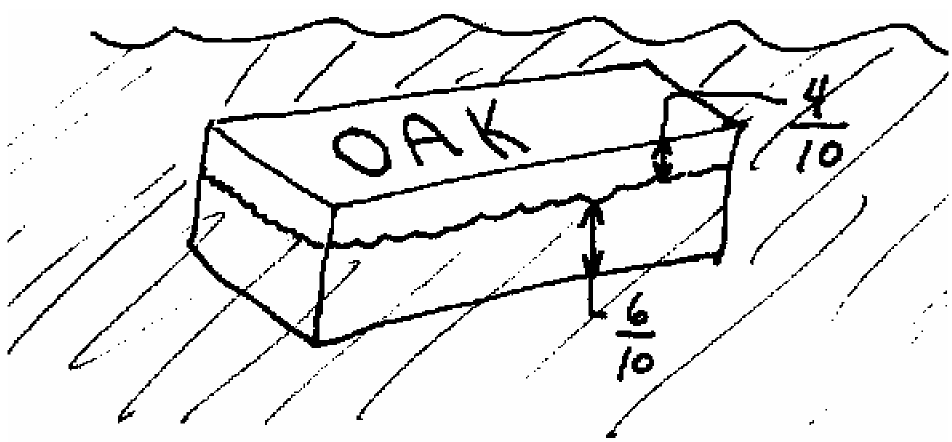


Pressure is a force that is distributed over an area, as in 'pounds per square inch' that you may read on a pressure gauge for the tires on a car. Lets say you have a 5 pound brick, and a cleared area of soft dirt in the yard. Lay the brick down on it's largest face, pick it up and you may see a small depression on the ground with a large footprint. Lay the same brick on it's short end, and you'll see a deeper imprint with a smaller footprint. If you could balance the brick on a vertically held nail and set the nail point on the ground, it will of course make the deepest imprint with the smallest footprint. This illustrates that the same force (weight of the brick, 5 lbs) can create larger pressures simply by reducing the footprint of the area thru which the force is channeled. Now, think of the atmosphere as an ocean of freely moving molecules, and you are at the bottom of that ocean. That's right, there is a column of air 50 miles high over you, and the weight of that column of air is on your head. That is where the atmospheric pressure of 14.7 psi (pounds per square inch) comes from. Since the air molecules are free moving, there must be an equal force sideways created by air to keep the vertical weight of the air from just crashing straight down. It has nowhere else to go, so the pressure must be the same in all directions. Because of these properties and others, air is considered a fluid, a very light and invisible one, but a fluid none the less. Bodies of water are similar, in that as you go deeper under the surface, there is a longer column of water to hold up in equilibrium. So as you go deeper, the pressure required to maintain equilibrium also gets larger. Just as in air, the water down there has nowhere else to go, and so the vertical pressure must be the same in all directions. This is called *hydrostatic* pressure.

Density and specific gravity

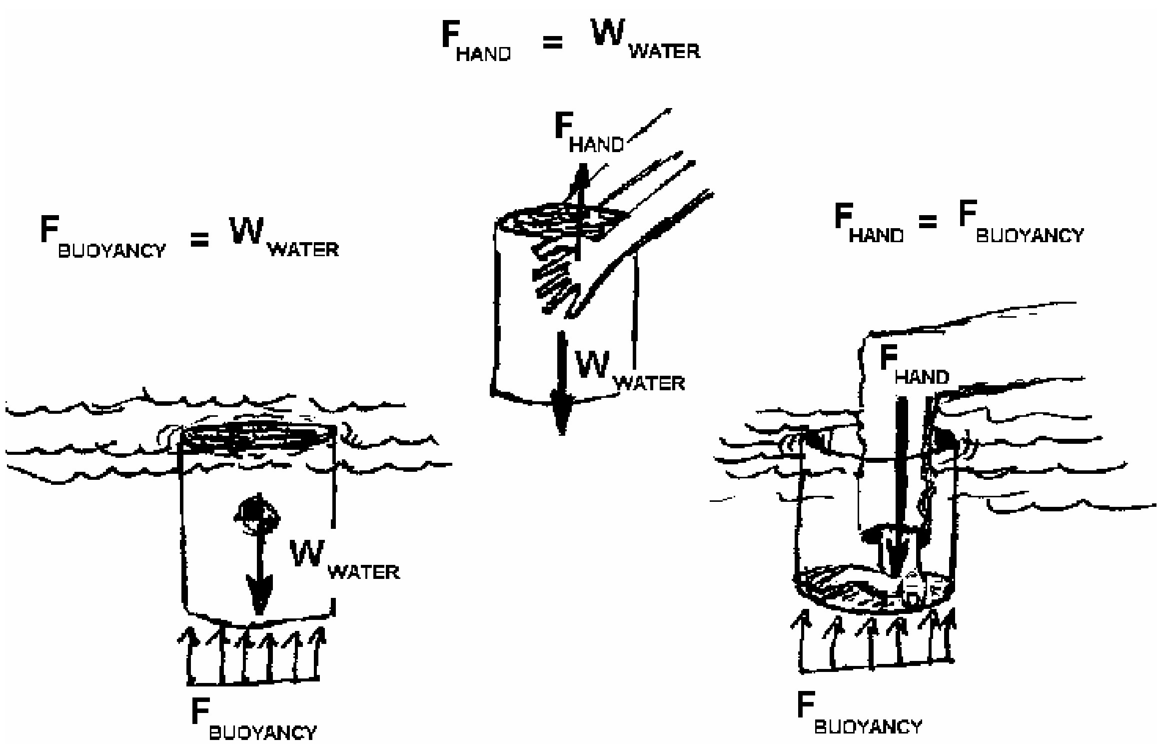
All materials have density. If they have mass, and occupy a certain volume (that just about covers everything…), then their density is the mass divided by the volume, as in kilograms per cubic meter. Solids and liquids have a more or less constant density characteristic to the particular material. Pure water has a density of 1000 kg/m^3, while a metal like lead has a density of 11344 kg/m^3.

Specific gravity has no units, as it is a ratio of density divided by the density of water. Water is a specific gravity of 1.0, lead 11.3, pinewood is 0.4. Materials that float have specific gravities between 0 and 1. For solid materials less dense than water, it is easy to determine the specific gravity. With a perfectly rectangular piece of material (say a block of oak), place it in water. About 6/10ths should be under water, and 4/10ths above, giving it a specific gravity of 0.6.



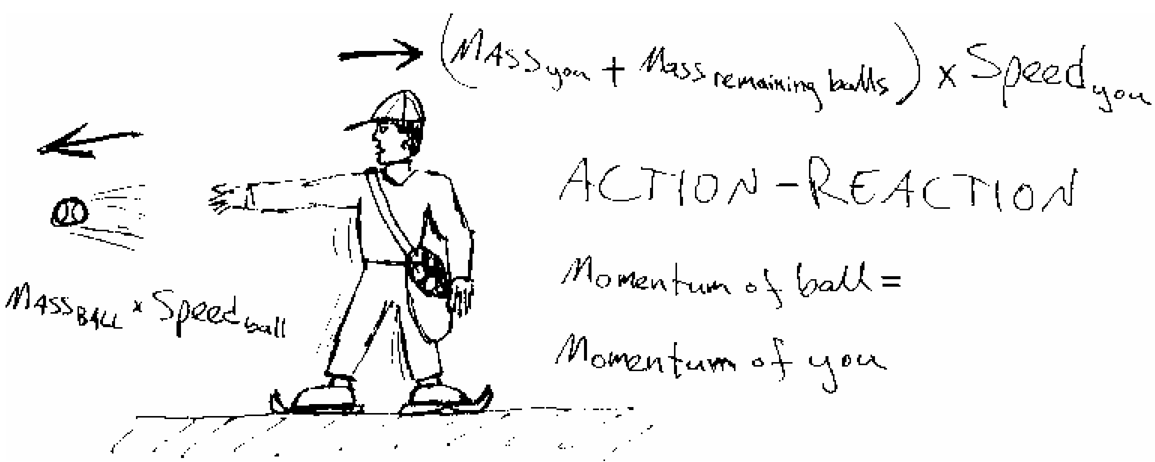
Buoyancy (Archimedes principle)

Eureka! That is what the Greek scientist-philosopher Archimedes is supposedly to have exclaimed when he discovered the principle explaining buoyancy. Take a light-weight plastic bucket and dip it into a swimming pool. Fill it to the brim so it just barely floats there in the water, without a care in the world. You tell yourself that the water inside the bucket must be in perfect equilibrium, as it is neither accelerating upwards nor downwards. It is perfectly at rest, which means the sum of all forces inside the bucket of water must equal to zero. You know the water has weight, in fact, you can pull the bucket up out of the water and feel the force of it's weight and measure it on the bathroom scale. But 'wait a minute', you say. The forces that act on the outside of the bucket must be pushing up with the same force as the weight of the water pulling down. Yes, that's true, but what if the water were not in the bucket (you dumped it out) and you forced the bucket back in the pool, pushing it underwater, just up to the brim but not enough to spill over the top. You feel an upwards force that feels suspiciously equal to the weight of the water you just had in the bucket. Understanding the principle of force equilibrium, you know that the upwards force had to be equal in magnitude yet opposite in direction to the weight of the water in the bucket during the first part of the experiment. *Eureka*! You just discovered the principle of buoyancy, that the upward force of buoyancy must be equal to the weight of water that is 'displaced' by a shape (volume) pushed down into the water. If you know the volume of a hull shape below the waterline, you'll know how much buoyancy it is capable of. Which means you'll know how much the ship can weigh (how much cargo it can carry) to be in equilibrium with the force of buoyancy.



Momentum and acceleration

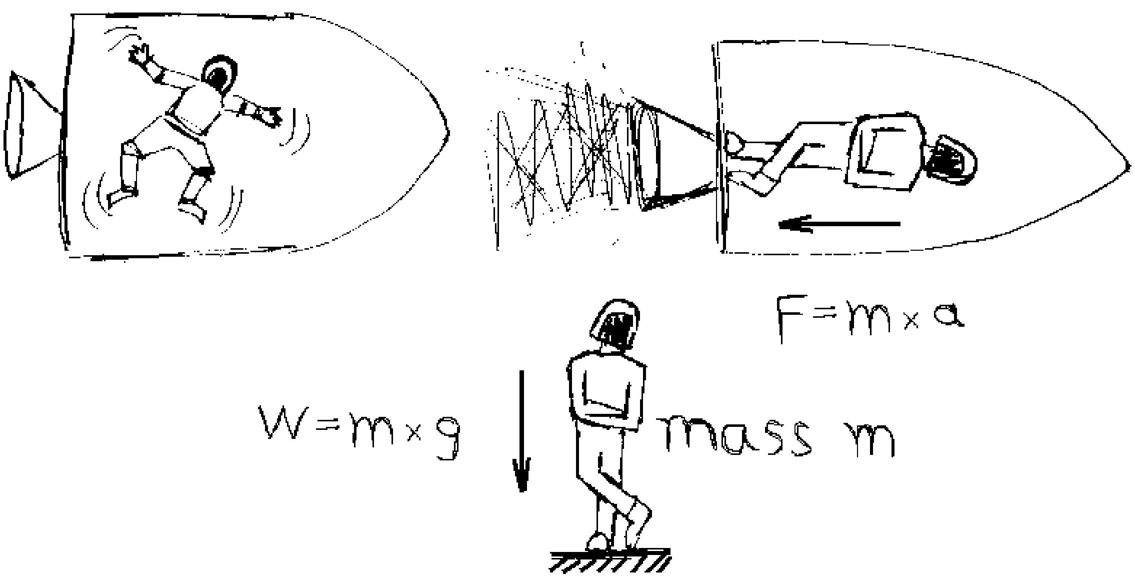
An object (read that as a 'mass') at rest wants to stay at rest until acted upon by a force. An object in motion wants to maintain that motion until acted upon by a force. My, my, it seems that forces influence everything! Of course all stationary objects on earth are at rest because the forces acting on them are in equilibrium. But put an unbalanced force on them and they move. Like your car, give it gas and you are pressed against the seat, or rather the seat is pressing against you with an unbalanced force and you start to move and accelerate forward. You were at rest, but now you are moving and it took a force to do it. You let up on the gas and cruise at a constant speed, no longer feeling the press of the seat. You are now an object in motion and you want to stay in motion. Stomp on the brakes, and you'll see what I mean. You had momentum, and to change that momentum required a force. Momentum can be expressed simply as: **Momentum = mass x speed**. Momentum is also conserved, meaning that you can't ever get rid of it, it can only transfer to other objects (masses). Consider that you are at the ice skating rink with a bag of baseballs slung over your shoulder. You throw a ball and *voila!* On your skates, you drift back a bit before the slight friction of your skates slows you down. You just experienced action-reaction.



You imparted momentum to the baseball where a moment before it had none, and in reaction to that momentum you moved in the opposite direction with an equal amount of momentum. However, since you are so much more massive that the baseball, your resulting speed is inversely smaller. If MASSball x SPEEEDball = MASSyou x SPEEDyou, then your speed SPEEDyou = SPEEEDball x (MASSball / MASSyou). If there were no friction, you would keep going at your new constant speed. Throw another ball and you will impart more momentum and consequently go even faster. Keep throwing baseballs continuously and you will smoothly accelerate, as well as have discovered the basis of propulsion!

Now, we have mentioned acceleration before, but what is it? Acceleration is defined as the rate of change of velocity. The car is going zero meters per second, then a second later it's going 5 meters per second, then another second later it's going 10 meters per second …Each second that goes by seems to bring with it an increase of 5 meters per second. That's an acceleration of 5 meters per second per second, or 5 m/s^2.

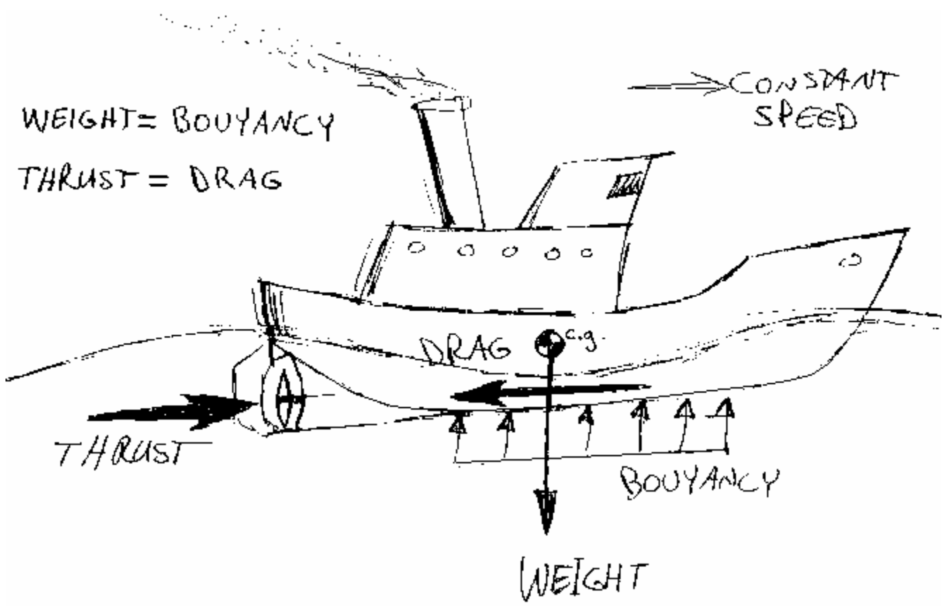
What's the difference between a force created by gravity (such as your weight, just stand on somebody and they'll tell you it's a force), and a force created by acceleration (in a car, for instance). Well, none actually. You could be in a space ship floating one minute, and squashed against the wall the next if the rocket motors are turned on. Inside the space ship, you can't tell the difference between a 'gravitational' force and a force on your body created by the acceleration of the rocket. It feels the same.



Hold a marble in your right hand and a brick in the other. Lift them up to a height of about eye level, and let them go at <u>exactly</u> the same time. They hit the ground at the same time, didn't they? So, you just did the same experiment that Galileo did. Well, sort of, but close enough. By doing a mental experiment, you can see why this is so. Pretend that you can chop-up the brick into small pieces that just happen to weigh the same as the one marble. Put the pieces in a tight bag and repeat the drop experiment. It still accelerates the same, whether the brick is in pieces, or the pieces are all 'holding hands' as one solid brick. Accelerating an object means that you are changing it's momentum continuously second by second. Which leads to Issac Newton's famous law, that force is equal to the rate of change of momentum. If the mass of an object is constant, then the rate of change of momentum becomes the rate of change of velocity, or expressed in the famous equation:
Force = mass x acceleration. In the case of gravity, the acceleration is a constant value (on the surface of the planet that is…) denoted as 'g', and g = 9.81 m/ s^2.

Force equilibrium at a constant speed

When you see a motor boat or cargo ship moving along in the water at a constant speed, it is in a force equilibrium. First, there is the equilibrium between the ship's weight and the force of buoyancy. It's not shooting up, and it isn't sinking, so it must be in some equilibrium in the vertical direction. In addition the propellers are creating a thrusting force by shooting water back behind the prop at a speed that the water did not have moments earlier. This constant rate of change of momentum in the water is imparted (by action-reaction) to the ship as a forward force. Since the ship is not accelerating, but only going at a constant speed, there must be some resistive force that is exactly equal to but opposite in direction from the propeller's thrust. That force is drag, and in water there are many forms of drag; viscous friction, pressure drag, wave drag, and windage.



Waves

We live with wave motion all around us, but fail to see it. We do hear it however! Sound is transmitted thru the medium of air using compression waves. What's that? You have had slinkys as a child no doubt. Ever let one person hold one end while you held the other end, and pumped the one end in and out? A compressed portion of the slinky could be seen to travel from you to the other end, even though the slinky as a whole did not move to the other end. The disturbance was 'communicated' to adjacent spring loops at a particular speed known as the wave speed. Ever stretch a garden hose to it's full length and 'whipped' a wave into it, to see it travel down the full length of the hose? That wave is a transverse wave, as the hose motion (the 'medium') is perpendicular to the direction of the traveling wave. Ah, how about the old 'throw the stone in the middle of the pond' trick. A nice circular wave (transverse) moving out and growing larger in diameter, but smaller in height as the finite amount of momentum transferred to the water by the stone is distributed over an increasingly larger area.

Waves can be single events, they can be propagated like a sine wave with multiple waves head-to-toe, or they can be created continuously which produces a phenomenon known as a standing wave.

<u>Basic electrical circuit theory</u>
You should become familiar with these three terms; current, voltage, and resistance. *Current* is the rate of flow of electric charge along a conductor, Coulombs per second, or more commonly known as Amperes (amps). The 'electrical fluid' is electrons in motion along materials that easily give up and exchange those electrons, such as metals.

Voltage is a measure of the potential amount of energy that can be imparted to each electric charge using devices like batteries or generators.
It takes an effort to push electrons around in a circuit, and the harder it is to push, the more *Resistance* is said to exist in the circuit.

I like to think of an electrical circuit as being analogous to water flowing between 2 ponds at different heights separated by a dam. The difference in height is the effect of the battery voltage, and there exists a potential for the water in the top pond to rush thru a sluice gate to the bottom pond. The greater the height difference, the greater the potential for the water to rush into the lower pond (voltage). But you control the gate, the resistance, and so can control the total current of water, the gallons of water per second that rushes thru. If you have infinite resistance (the gate is closed), then the current is zero. Once the top pond is emptied, it's as if the battery were dead, all of it's stored electrons spent.

A direct-current (d.c.) electrical circuit has a source of energy, such as a battery, a circuit resistance, and a current that flows thru the circuit. If an electrical circuit has many different resistances in series, then you could think of it as many in-line waterfalls with each fall at different heights corresponding to the voltage potential lost at each drop of height. The total voltage of the circuit is the height of the highest water fall up stream minus the height of the lowest waterfall down stream. There is a relationship between voltage, current, and resistance, known as Ohm's Law: Voltage = Current x Resistance. Also, in a circuit, the sum of all the voltage drops across each series resistance must equal the voltage of the energy source (the battery), which is called Kirchhoff's voltage law.

Chapter 3 Ships

Ship parts, nomenclature

The hull of course is the most basic part of the ship. It creates the exterior shape that displaces the water to achieve buoyancy. It needs to be able to crash thru the waves and have sufficient 'reserve buoyancy' that it won't get swamped (water pouring over the sides, sinking the ship). The bow has this job, and it needs to slice the waves above the waterline and push the water aside smoothly below the waterline, and lift the nose of the ship quickly should the wave be too high. The stern needs to smoothly reintroduce the water traveling under the ship back to the surface, especially about the propeller and rudder. The deck house 'superstructure' houses the crew, and provides the necessary visibility to see and be seen for proper navigation. See the model ship line drawing for the essential parts of a ship.

Displacement hull

A cargo ship is a displacement hull; it has to plow its way thru the water instead of skimming over the surface. A displacement hull stays afloat by displacing water weight equal to the ship's weight, creating a 'static' equilibrium of forces.

Planning hull

If you have seen a motorboat, then you have seen a planning hull. When the boat is slow, it is acting as a displacement hull, but as it gets faster and faster, the boat creates tremendous drag as it starts to climb uphill over the bow wave. Finally, it crests the top of the bow wave, slides down the front side of the wave and moves faster than the bow wave can catch up. It is on a 'plane' at this point, and the reason the boat does not sink down to it's zero-speed waterline is that the water cannot move away fast enough due to the speed of the boat, and so imparts a lifting pressure to the bottom of the hull. This is known as hydrodynamic lift. A water skier uses hydrodynamic lift to stay afloat while in motion, but remove the speed and the skier sinks (not being in addition a displacement hull).

Hydrofoil

A hydrofoil takes the planning hull concept one step farther by adding actual wings under the hull. In the same way an airplane achieves lift with air flowing over the wings, so the hydrofoil does with water flowing over its water wings. The difference from the planning hull is that lift is achieved with lower pressure over the top of the wings 'sucking' the boat up as opposed to higher pressure on the bottom of the hull pushing the boat up.

Chapter 4 Hydrostatics

Center of buoyancy

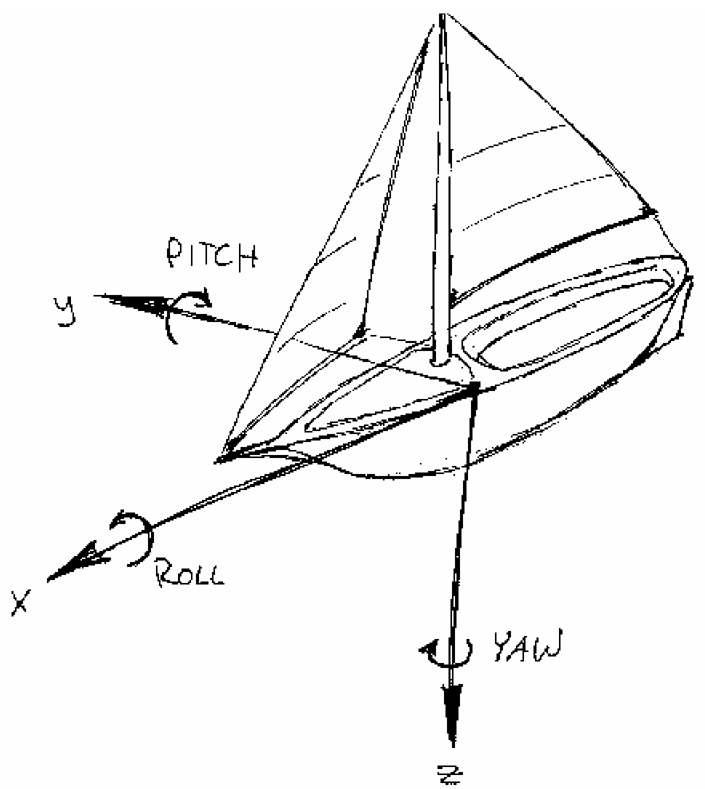
The center of buoyancy is similar to the center of gravity in that it represents the balance point of all buoyant forces acting on the submerged portion of the hull. Unlike the center of gravity (which remains fixed), the center of buoyancy shifts side to side and rocks forward and backward as the hull rolls and pitches in the water. In this case, the submerged portion of the hull is always changing shape due to the action of waves and wind rocking the boat.

Hydrostatic pressure

Take a long pipe whose circular cross section has an area of 1 square inch. Make it 30 feet long. From a boat, plunge it straight down into the sea, until the top is just flush with sea level. Don't let go! Ask a friendly fish who just happens to be swimming by to cork up the bottom of the pipe for you. Pull it out, then pour out the water into a bucket. Now weigh it. It says 15 lbs, more or less, doesn't it? So, if you were that fish who kindly corked up the pipe, for every square inch on your body you would feel 15 lbs of force pressing in on you *in addition* to the already 14.7 lbs per square inch the atmosphere is pressing down on the sea's surface. 15 lbs is the weight of a 1 square inch column of water 30 feet high, which is supported in a force equilibrium using pressure. This is called hydrostatic pressure, and becomes higher the deeper you go below the surface due to the weight of water above you.

Roll, Pitch, and Yaw

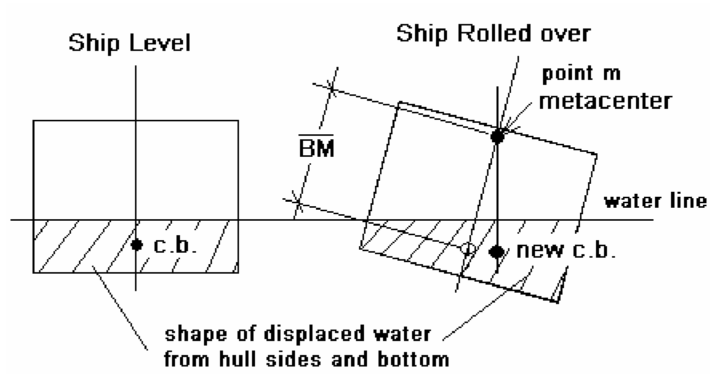
Roll, pitch and yaw refer to rotational directions with respect to the boat's frame of reference. Rolling side to side makes you seasick. Pitching up and down is fatiguing. Or exhilarating, depending on the moment.



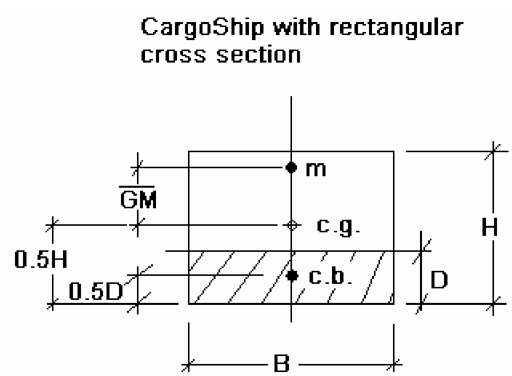
Roll Metacenter and Stability

First, what is the metacenter? It must first be understood that a submerged shape (such as the portion of the hull below the waterline) has a center of buoyancy, the balance point of all the buoyant forces on the submerged shape. When the ship rolls to one side, the submerged shape of the hull below the tilted waterline changes. This usually results in the center of buoyancy shifting over in the same direction as the roll. If one were to draw a vertical line thru the center of buoyancy (c.b.) in the rolled over condition, where it intersects the vertical line thru the c.b. when the ship is perfectly level (no roll), that point is the metacenter (point 'm').

Definition of Metacenter



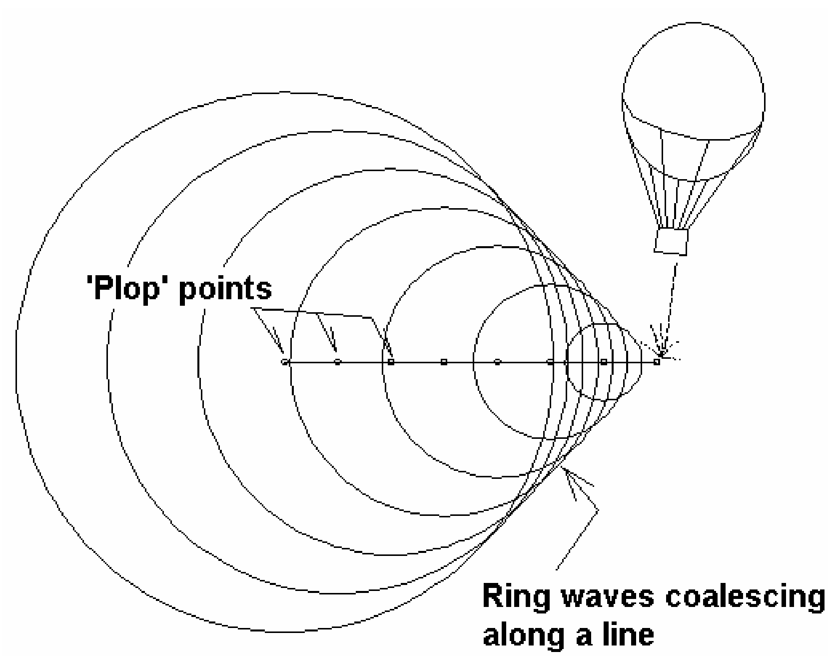
Since the vast majority of the total weight will be cargo, you could consider the ship as being a block of pinewood having the top-view shape of the hull. Pinewood has an average specific gravity of 0.4, which means that 40% of the block-of-wood hull height will be submerged below the waterline, 60% of the height will be above the waterline. With a cargo ship shape, the cross-sectional shape can be approximated as a rectangle. Thus the level center of buoyancy (c.b.) is in the exact center of the rectangular shape that is below the waterline (cross-hatched in the illustration). The center of gravity (c.g., the weight balance point) of the rectangular block of wood is in the exact center of the block. If the c.g. is above the metacenter, the ship will roll over. If the c.g. is below the metacenter, the ship will be presumably stable, at least for small roll angles.



Chapter 5 Hydrodynamics

Wave systems

The bow of the ship creates wave patterns, as does the stern. To think of how the bow creates a wave pattern, consider that as the bow moves thru the water that it is 'disturbing' new water continuously. Pretend you are just floating a couple of feet over smooth water in a hot air balloon, moving gently with a steady wind at a constant speed. You have a bucket of pebbles, and you are dropping a pebble into the water once a second. You are not disturbing the water continuously, but rather with discrete, individual plops. Each plop of a pebble creates a ring wave that we are all familiar with. Knowing that the ring waves grow in diameter with increasing time, we notice that the ring waves created with the first dropped pebbles are larger that the ring waves from the most recent 'droppings'. They are also forming a pattern. Directly behind you the water is a little choppy, seemingly chaotically. But, somewhere off to your left and right, is a clearly visibly and steady V-shaped wave keeping pace with you in the balloon. This 'standing wave' is composed of the crests of all the ring waves that are acting in concert with each other, constructively adding to each other. The illustration should show you why this is.



The bow of a ship is 'plopping' the water continuously, as is the stern. Together they form a complex interacting wave pattern. The standing waves formed by the coalescing ring waves have the speed of the ship, which gives the waves a certain length as the wave length of water is related to the speed of the water wave. These two wave systems (bow, stern) try to add or subtract from each other in what is known as constructive or destructive interference. There comes a speed where the front wave pattern severely interacts with the rear wave pattern, and a deep trough with a wave length of one boat length is created. This 'wave drag' is what keeps displacement hulls limited to slow speeds. At this point to go any faster, the boat has to climb uphill over it's own wave, which a cargo ship cannot do.

Hull speed

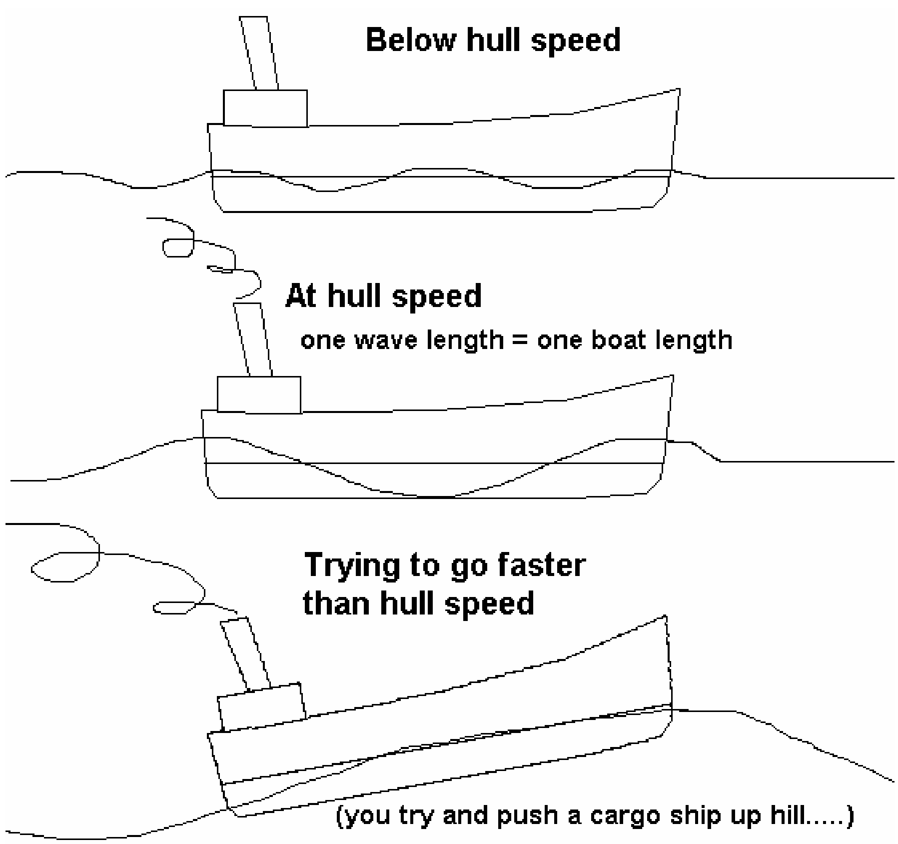
This natural speed limit for displacement hulls is known as the "hull speed". For a displacement type hull, the longer it is, the faster it can go, proportional to the square root of the waterline length.

There is a dimensionless ratio which describes the number of waves per boat length, and that is the 'Froude Number' = Fn . The waves in question are the standing bow wave system created by the coalescing ring waves. When Fn = 0.4, a water wave length is equal to the boat's water line length 'L'. Hull speed is then defined as when Fn = 0.4.

$Fn = Speed / [g \times L]^{0.5}$ where g = acceleration of gravity = 9.81 m/s^2, Speed (m/s), L (m)

Rearrange: $Speed = Fn \times [g \times L]^{0.5}$

Hull Speed (m/s) = $0.4 \times [g \times L]^{0.5}$



Two wave lengths along the hull means it is traveling at ½ hull speed, 3 wavelengths 1/3 hull speed, etc…

Wave drag

Wave drag is the resistance to forward motion by the wasteful transference of momentum to water in the form of surface waves, which then dissipate the energy by radiating away from the ship. Between zero speed and hull speed, the wave drag associated with the ship's own wave system increases approximately to the 7th power of speed. Expressed in the dimensionless ratio of the Froude number, the 'calm weather' wave drag is approximated:

$Drag_{WAVE} = 16.778 \times Fn^{7.164} \times g \times \Delta$ Newtons of force

Where g is the acceleration of gravity 9.81 m/s/s

Δ is the loaded mass (mass displacement) of the ship, kilograms

Additional wave drag is realized by other waves present on the water's surface bashing against the bow of the ship. For rough choppy water, added wave drag is approximated:

$Drag_{WaveAdded} = 0.000485 \times [(L / (V_{DISP})^{1/3})^{1.89}] \times g \times \Delta$ Newtons of force

Where L is the waterline length of the hull, meters

V_{DISP} is the volume of water displaced by the hull (volume displacement), cubic meters

g is the acceleration of gravity 9.81 m/s/s

Δ is the loaded mass (mass displacement) of the ship, kilograms

Viscous drag

This type of drag is friction, the 'stickiness' of water against the hull sides. Microscopically at the hull surface, it looks like a mountain range compared to the water molecules flowing past. These molecules have a much lower speed than the water farther away from the hull surface since they have to negotiate the molecular mountain range. In fact, one can argue that the speed of those water molecules right at the hull surface is zero relative to the hull, where as those a few millimeters away are going the full speed of the ship. This slow, lazy zone is called the 'boundary layer' in fluid dynamics, and thinking of action-reaction, this boundary layer represents a change in momentum in the water, water that gets dragged along with the hull. That momentum wasn't there seconds before, now for a time it's moving with the hull. That continuous change in momentum in the water manifests itself as a friction drag force on the hull. The thicker the boundary layer, from longer lengths of hull surface, or greater surface roughness (a larger molecular mountain range), the more momentum is lost to the water, so the greater the drag force. Viscous drag force is proportional to the 'wetted' area (surface area in the water), and to the square of the water speed:

Viscous friction drag of the hull:

$Drag_{HULL} = \frac{1}{2} \rho_{WATER} \times Speed^2 \times A_{WET} \times C_F$ Newtons of force

where C_F is the skin friction coefficient, $C_F = 0.005$ for model boat sizes,

Awet is the wetted area, meters squared

Speed is the boat's speed, meters per second

ρ_{WATER} is the density of water, 1000 kg per cubic meter

Chapter 6 Optimizing the cargo ship design

Predicting efficiency with trade studies

A trade study is where you get to do 'what if scenarios'. What if the length to beam ratio was such and such, how would the freight rate change (the so-called 'performance metrics')? You pick the 'trade space', that is the variables you are willing to vary, and you affirm the constraints (the things you can't change). You state the relationships between all the variables and constraints, then alter the freight rate equations so that they are expressed in terms of your variables and constraints. Now, at that point, you can do the what if stuff and discover the most efficient design, the one with the cheapest freight rate. First pick the trade space…..

Trade Space:

Draft = D, Beam = B, Length = L
Number of Motors = Nmotors
Number of battery packs = Nbatteries
Propeller Diameter
Propeller Pitch
Gear reduction

Constraints:

Sum Total = T = L + B = < 66 inches

D = < 5 inches

Length to Beam ratio (L/B) is constrained to: 3 = < (L/B) = < 6

Metacentric height above center of gravity GM >= 0.75 inches (suggest 1 inch)

Freeboard > = 3 inches (suggest 5-6 inches to keep from swamping)

Bridge deck height from Freeboard line > = 5 inches

15% of the length L must be decked, (5% must be for the deckhouse, leaving 10% for the foc'sle)

Voltage per motor = < 12 volts

Cargo Container sizes, 1x1x4, 1x1x2, or 1x 1*(integer multiple) x 4*(integer multiple)

Distance traveled = ~60 meters (200 ft)

Density of wood cargo = 0.4 (pinewood)

Performance Metrics:

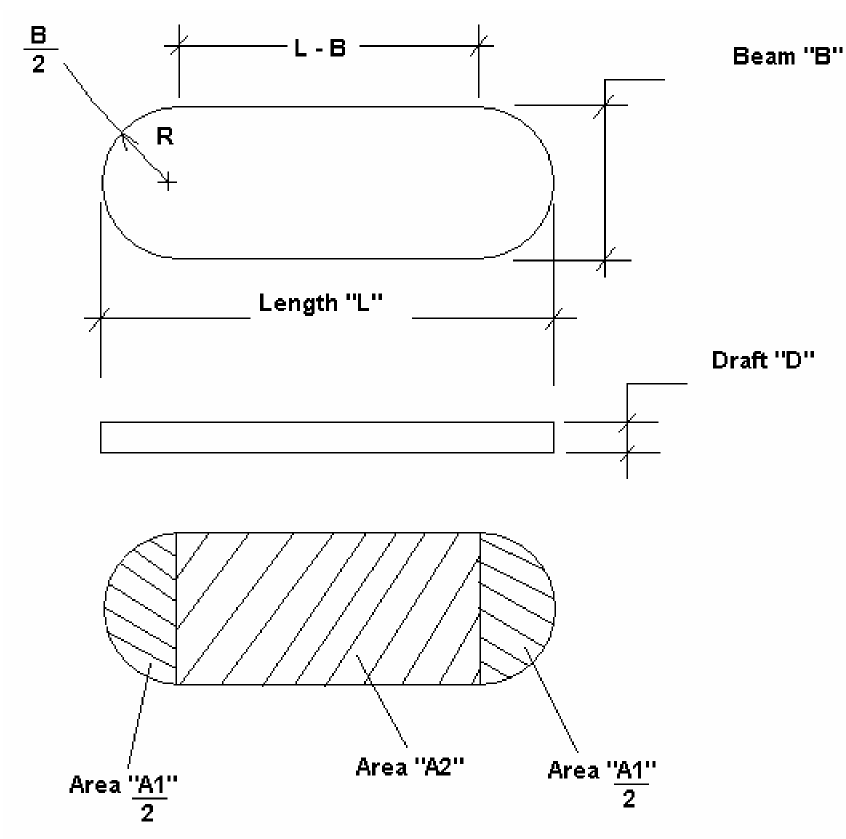
Minimize the Freight Rate = [Fixed Costs + Operating Costs] / [Total Cargo x Distance Traveled]
Where Distance Traveled is in feet, and Total Cargo is in number of 1"x1"x4" containers

Fixed Costs = \$10 x L x B x D (L,B,D in inches)

Operating Costs = \$10 x Time to run course, seconds x Number of motors

Parameterize the Performance Metrics

Make Freight Rate = a function of (T, D, B, L, Nmotors). Vary parameters to minimize Freight Rate.
First, start by making an approximation model of the ship's shape that is under the water that is easily described with an equation.



Next, form basic relationships to determine the hull displacement (weight of water displaced by the shape of the hull below the waterline. Remember Archimedes principle, that the buoyancy force is equal to the weight of water displaced.

$A1 = \pi B^2 / 4$

$A2 = B \times (L - B)$

Displacement volume = Volume = $(A1 + A2) \times D$

Water Density = ϱ = 1000 kg / m^3

Displacement weight = Δ = Volume $\times \varrho$

Next, add the effects of the constraint: L + B = a constant = T = 66 inches

The beam as a function of the L/B ratio and the constraint T: B = T / (1 + L/B)

The length is easily: L = T – B = L/B x [T/ (1 + L/B)]

The stability requirement for the metacentric height GM >= 0.75 inches will dominate the design. This will determine the minimum beam required for the draft desired. Thus draft D becomes the '**master parameter**', driving the beam, and with the constraint of L+B = 66, the length is lastly determined. Furthermore, the L/B ratio must be between 3 and 6.
To keep the ship from rolling over, the metacenter must be higher than the center of gravity. To gain some margin over this, an additional ¾ of an inch is required by the rules.
From the illustration, knowing the specific gravity of the cargo (pinewood) leads to the draft: D = specific gravity x H. Or, if you know the draft D, the height of cargo H is: H = D / specific gravity.

The equation for the metacenter height above the center of gravity (GM) can be easily derived for a rectangular cross-section, and is given here:
GM = ½ x D x (1 – 1/specific gravity) + B^2 / (12 x D)

If GM is given (as in the rules, GM = 0.75 inch), then we can solve for the minimum beam B required for any draft D:
Minimum allowable B = square root [(GM – ½ x D x (1 – 1/specific gravity)) x 12 x D]

And so the length of the ship L = T – B, where T = 1.676 meters (66 inches).

Divide the length L by the beam B and determine the L/B ratio and check that it is within the recommended limits of no less than 3, no more than 6.

Taking all these equations, it is possible to calculate and tabulate safe working dimensions for the model ship that will be stable.
These tables represent the maximum safe draft D and the minimum safe beam B for different L/B ratios for the given specific gravity of the cargo. Also, the length L, displacement weight, and cargo height H are tabulated. This is based on a more conservative stability requirement, just for extra safety, by making GM = 1.0 inch instead of the minimum 0.75 inch as required by the rules. A glance at the table shows an L/B of 6 will not satisfy the minimum draft required in the rules, 3" (76mm), yet at greater than 64 mm it will fail the stability criteria.

Pinewood cargo

SPECIFIC GRAVITY = 0.4 GM = 25mm	L/B = 3	L/B = 4	L/B = 5	L/B = 6
Draft D, millimeters (mm)	124	96	77	64
Beam B, mm	420	335	277	237
Length L, mm	1256	1341	1399	1439
Displacement weight, kg	62	40.8	28.6	21
Safe height H of cargo stack, mm	310	240	192	160

We will make the assumption that the motors are big enough and the prop selection efficient enough that we can comfortably operate the ship at near the hull speed, so we set the Froude Number Fn = 0.35. This assumption will be tested later on when we size the motors/propellers to see if this was a good or bad assumption.

Speed = 0.35 x $[g \times L]^{0.5}$

The time to traverse the course is easily: Time = Distance / Speed, where the distance is given at ~ 60 m. One can add acceleration terms, knowing that 3-5 pounds of force will propel the model ship forward. There will be extra time spent in speeding up to the hull speed, and time to slow the ship down, and any maneuvering about 'in port'.

NOW, all the equations describing Length, Beam, Displacement, Speed, and Time, have been made functions of T, GM, cargo specific gravity, and D. Stick all of this into the equation for Freight Rate, which is the *figure of merit* by which the ship's objective performance will be judged (plus the beauty contest which is subjective).

The ship's displacement weight Δ = ship's empty weight + cargo weight = We + Wc

We can estimate the empty weight, We, which is the weight of the motor + batteries + radio control equipment + hull structure. The hull will probably vary from 3.5 to 4.5 kg, and the motor, batteries, radio are about 3.5 kg.

Rearrange: cargo weight Wc = Δ - We

The number of containers (Ncontainer) carried in the model ship can be estimated by taking the cargo weight and dividing by the weight of one cargo container which is the volume of one container times it's density. The cargo density = cargo specific gravity x density of water. The volume per container = 1"x1"x4" cubic inches.

Fixed Cost = 10 x D x L x B (dimensions D,L,B in actual measured inches)
Operating Cost = 10 x Nmotors x Time (time measured in seconds)

Freight Rate = [Fixed Cost + Operating Cost] / [Ncontainers x Distance]

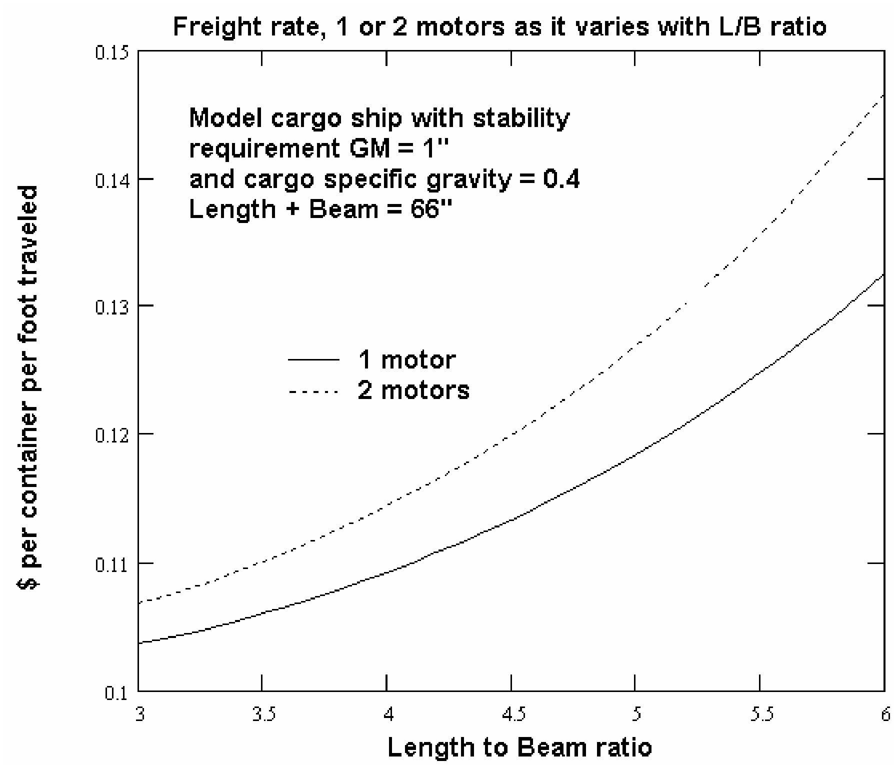
(Distance in feet, ~ 200 ft)

Also by running the numbers, using the maximum value for T = 66" (1.676 m) gives the better Freight rate, but there might be a subtle trade off here between making it as large as possible and perhaps needing 2 motors, or making it slightly smaller and using one motor.

Not mentioned so far, but just to be complete, I should mention that the most efficient ship will have the thinnest walls, so that the vast majority of the internal volume is used for cargo containers, not for unnecessary hull structure. The hull should be made of 1/8" thick material, no more. It can be plywood, epoxy-coated cardboard, fiberglass, or a skin covering a light framework. Hulls made from foam usually have very thick sides and bottom, making them very inefficient.

With constraint T fixed at 66 inches, we can vary the master parameter D for freight-rate cost and L/B ratio. So, making a graph of Freight Rate (y axis) vs L/B (x axis), and for Nmotor = 1, and Nmotor = 2, we come up with this final graph.

Model Cargo Ship, for L+B = 66 inches, GM = 1 inch, pinewood cargo



The general trend is that the smaller the L/B ratio, the lower the Freight rate costs.

Also, the more motors in the ship, the slightly more expensive the Freight rate.

The total variation is 14.5¢ at L/B =6 and 2 motors, to 10.5¢ at L/B =3 and 1 motor. That is a 38% variation from one extreme to another, not a whole lot to get excited about, but enough to get your attention (if you are a bean counter).

A L/B of 4 or 5 and 1 motor gets you a relatively light and maneuverable ship, at 11¢ per container per foot traveled, a pretty good compromise, as one motor should be able to easily move such a light ship at higher than normal speeds.
Remember, this is <u>just the start</u>. After these trade studies, you now have to build the hull, integrate the propulsion system (a science all to itself), the rudder and controls, the radio control, the batteries and other electronics and switches. It will be a miracle if it works at all. If it does, you will need to learn to pilot it. Good handling qualities as well as looks with a good report to document your thinking, drawings, the construction phase, the testing of ideas, innovations, and presentation quality will determine your success.

Chapter 7 Propulsion

Propellers

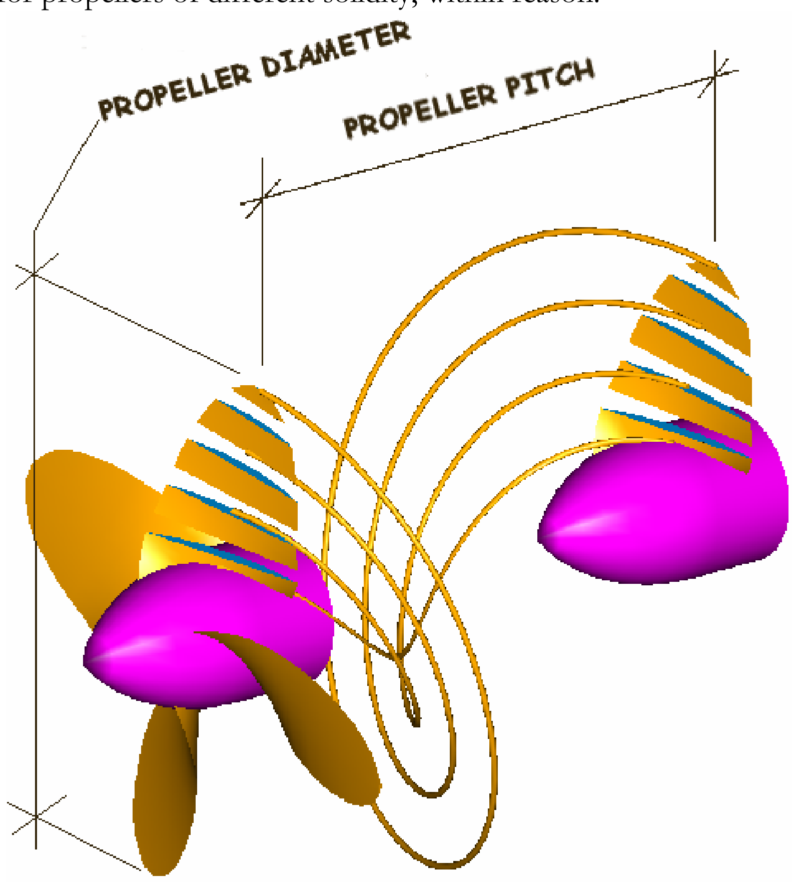
Props provide the mechanical means by which motor torque and spin speed can be converted into thrusting force by continuously adding momentum to water; water is sucked in then jetted out at a speed it did not have before, which manifest itself as a thrust force.

A propeller has 3 basic measurable quantities that characterize them:

1) The overall diameter 'Dprop'

2) The screw pitch of the helix, 'Pitch', which is how far the propeller can screw forward in one rotation based on the blade twist angle, and no slipping. Generally the twist distribution from root to blade tip (high at the root, decreasing towards the tip) is such that all radial positions have the same pitch distance.

3) The solidity 'σ', which is the total blade area (were you to untwist it, lay it down flat and measure the area) divided by the propeller disk area (πR^2). This is a measure of how 'full' the propeller is, as in 2 long-skinny blades, or 3 short-wide blades. A propeller with greater solidity will have more 'bite' because there is more of it for a given diameter, but because of other considerations, solidity ranges from 0.3 to 0.4 mostly, but model propellers seem to go higher, past 0.5. Available test data for one prop design can be adjusted for propellers of different solidity, within reason.



Propellers must be matched to the motor/engine driving them. The prop is most efficient at a particular forward speed with a particular RPM (revolutions per minute). It will provide a particular thrust and require a certain amount of torque under those conditions. Likewise, an engine/motor should be 'happy' at that particular RPM, and be able to deliver the required torque to spin the prop. If not, then perhaps using a transmission with a gear ratio to change the torque and output speed of the engine/motor can improve things, and then again maybe not. The prop requires a certain amount of mechanical power (prop torque X prop spin speed), and the engine only has so much power available (engine torque X engine spin speed). Transmissions can change the output speed of the engine, but only at the cost of also changing the available torque such that the same amount of power is being transferred. Here is where careful matching can payoff handsomely.

Cavitation

One problem that props face is cavitation. Cavitation occurs when the prop creates so much low pressure over the suction side of the blades that the water actually 'boils' to a gas (normal temperature, but low pressure) and the prop ends up spinning in a self made bubble, breaking down it's connection with the water. No thrust, as no water is being accelerated thru the blades. More commonly, it occurs when the prop is too close to the surface of the water, and it 'sucks a bubble' from the surface, the way your kitchen blender does when the vortex in the middle reaches down to the choppers, then all blending ceases. Same in a prop too close to the surface, all thrust will cease. Outboard motors use what is known as a 'cavitation plate' above the prop, making it more difficult for a bubble to be sucked down. If the prop is positioned below the hull, with a 'roof' over it's head, the same protection will happen as with a cavitation plate. More about good propeller placement will be mentioned later.

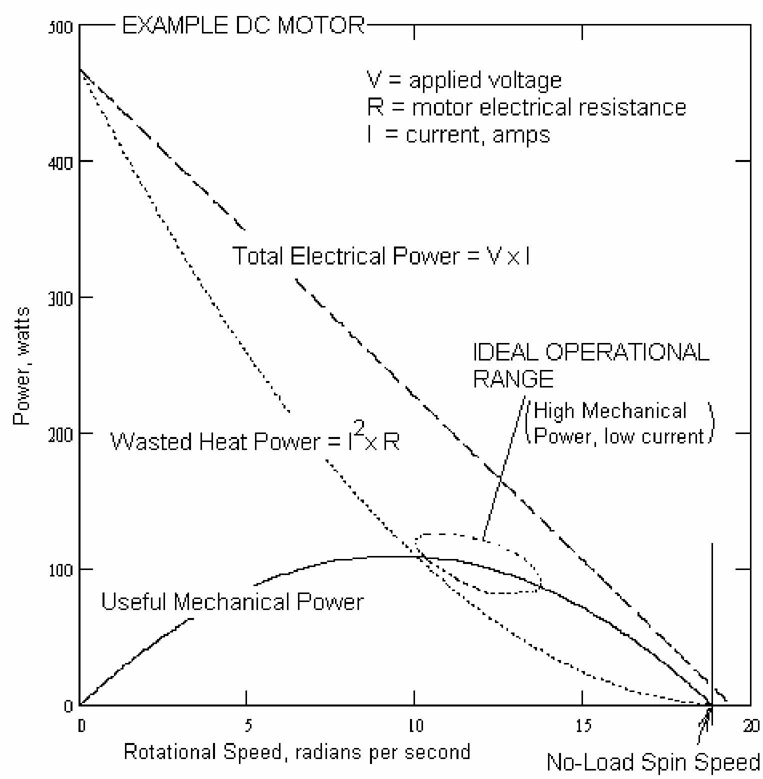
Electric motors

A motor is a device where electric energy is converted to mechanical energy, plus wasted heat energy. Similarly, a generator is a device where mechanical energy is converted to electric energy, plus wasted heat energy. There is always wasted heat energy when converting from one form of energy to another.

Thus a motor/generator are really one in the same device, with a reciprocal nature:
'Motor mode'; electric current input, torque and rotational speed output.
'Generator mode'; torque and rotational speed input, electric current output.

A motor is a generator, and a generator is a motor, depending on whether mechanical or electric energy is being supplied. When a motor is being driven with electric current to produce torque, it also generates a back-voltage (in the 'generator mode') due to the rotational speed of the rotor shaft. At a particular high rotational speed, the generated back voltage is equal to the applied voltage from the battery. This is the 'no-load speed', the fastest the motor can go for the given applied voltage, but it has zero torque at that point, and if there were no internal friction, the electrical current would be zero. It is creating no useful power in this condition. On the other end, the motor creates the maximum torque when the rotor shaft is held still (rotational speed = 0), and has no back voltage generated. This is also creating no useful mechanical power, as nothing is moving. It is all wasted as heat energy.

This is a graph of a large electric motor, its total electrical power, the dissipated wasted heat power, and the mechanically useful power. The values vary with rotational speed due to the back voltage generated.



It can be seen that there is an optimum rotational speed where the mechanical power delivered is the greatest, and that speed is equal to ½ of the no-load speed. Right smack in the middle. Who would have guessed? Also, the maximum useful power at ½ no-load speed is equal to ¼ of the maximum electrical power at rotational speed = 0. This relationship allows us to rapidly estimate the mechanical power available from the motor to compare against the power required to push the hull at the design speed.

With voltage V, electric current I, and resistance R, the total electrical power = V x I. At zero rotational speed (no back voltage to worry about), using Ohms law ($V = I \times R$ or $I = V / R$) the electrical power = V^2 / R.

A propeller cannot transmit 100% of the motor's mechanical power to thrust the ship, as there are always losses and inefficiencies with energy conversions. The best you can hope for with a marine propeller is about 80% efficiency, or $\eta_{PROP} \sim 0.8$. Motors have internal friction and other losses, but are fairly efficient (except for the heat losses), the motor mechanical efficiency $\eta_{MOTOR} \sim 0.86$. If there is a gearbox, there are frictional losses internally, so you don't get all the torque out that you would like. Even if there is no gearing, a direct drive to the propeller still has some friction in the propeller shaft tube. Assuming that the gear ratio = 1 for simplicity of design, make the gearbox efficiency $\eta_{GEAR} \sim 0.98$.

So now we have an estimate of the best power available per motor to thrust the hull:

$$P_{AVAILABLE\ BEST} = \frac{1}{4} [V^2 / R] \times \eta_{PROP} \times \eta_{MOTOR} \times \eta_{GEAR}$$

For a given motor and voltage, this is the best you can do, no matter what. Period. In fact, it is most likely that the perfect 'optimum' propeller will never be found, for they are impractically large and slow turning. $\eta_{PROP} = 0.65$ is closer to the mark. The only things that can be done to improve best power available, is to choose a larger motor, apply a larger voltage, or use multiple motors. You cannot just up the voltage on any given motor, as they are rated for only so much power before you burn them up! This assumes that you will find a propeller with the right shape that operates efficiently at the optimum rotational speed = ½ no-load speed. It's actually better to operate at a little higher speed than the optimum. The reduction in mechanical power is minimal, but the current draw is much lower, giving longer life to the battery and the motor will run cooler. If not, you can gear it up or down to suite the needs of the available 'off-the-shelf' propeller. Much performance improvements can be achieved with a gear box, if the output of the motor needs to be converted from high torque/low RPM to low torque/high RPM, or vise-a-versa.

A d.c. (direct current) motor has 3 basic measurable quantities that characterize them:

1) Electrical resistance across the terminals R_{MOTOR} (ohms)
2) Torque capability per amp of current, known as the motor torque constant K_T (N-m/amp)
3) The no-load current I_{NL}, a measure of the internal frictional losses. When the motor is spinning at it's top speed with no torque load, there is still a trickle of current running, such that the last gasp of torque that the motor is producing is just balanced by the internal friction.

There is another quantity known as the back-emf constant (electro motive force) K_B, which is it's ability to act as a generator and produce an opposing voltage as the shaft is spinning. It's units are volts per radian per second. Since it is the same physical property (remember, a motor is a generator which is a motor….), the two quantities are identical, and are numerically equal to each other when using metric units. In units other than metric, they differ by a constant multiplier.

The motors supplied by the museum look suspiciously like an old automobile windshield-wiper motor. They are 12V, high torque, low speed motors which can be used without gearing for the model boat competition. These are the motor's properties:
Resistance R ~ 0.4 ohms
Motor torque constant ~ 0.029 N-m/amp
No-load current ~ 1 amp
Optimum shaft speed ~ 1888 RPM at 12Volts

Running the motor/prop at 2000 RPM would be ideal. A good prop to use is a 2.75" diameter with a 4" pitch, with no gearbox. If the exact prop cannot be found, find one where the diameter^2 x pitch is approximately equal to 2.75^2 x 4 (~ 30).

Gears
Gears are a method for altering mechanical advantage, but they still transfer the same mechanical power. That is, one can have a high rpm and low torque for the input end of the gearbox, with low rpm and high torque at the output. Think of a car engine screaming at 4000 rpm, but the drive wheels are not going anywhere near that speed because the engine's power is converted thru the transmission gears to match a reasonable wheel speed. Except for frictional losses in the gearbox, the mechanical power in (TORQUEin x RPMin) is equal to the mechanical power out (TORQUEout x RPMout).

Chapter 8 Propeller-motor-hull speed performance predictions

Mechanical power is defined as Force x Speed for linear motion, and Torque x Rotational Speed for rotary motion. The units are the same, N-m/s, or watts. Electrical power has the same units.
The basic and simple idea for this chapter, is to be able to graph the mechanical power *available* from the propeller/motor/battery combination, and graph the mechanical power *required* to push the ship's hull thru the water. The power required will increase with greater water speed. We will then see at what speed the power available matches the power required, as this will tell us the top speed we can expect from the ship. We are assuming here that the propeller will be optimized so as to be able to transfer the maximum power efficiently at that maximum speed (which is usually not the case in reality). This will be our top-end number, the ship will never go faster than this speed.

Power Required
In chapter 5, the drag elements of wave drag and viscous drag were described and equations given. Power required to drive the ship is then Speed x (sum of all the drag elements).

Power Available

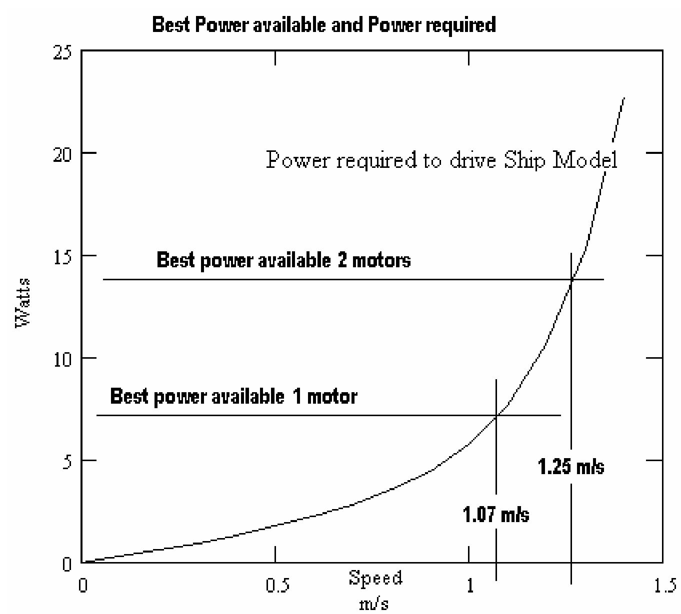
The power available to drive the ship was given earlier for the best case as:

$P_{AVAILABLE\ BEST} = \frac{1}{4}\,[V^2 / R] \times \eta_{PROP} \times \eta_{MOTOR} \times \eta_{GEAR}$

Where V is the battery voltage, R is the motor's electrical resistance (ohms) as measured across the motor terminals, and the efficiency factors η are approximately:

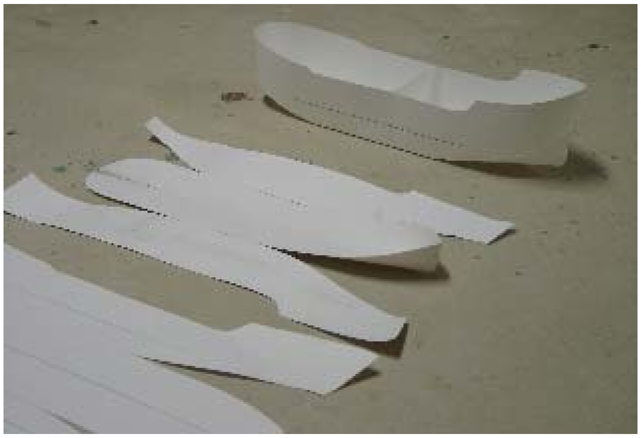
$\eta_{PROP} \sim 0.75, \quad \eta_{MOTOR} \sim 0.86, \quad \eta_{GEAR} \sim 0.98$

One can then graph the power required, and also draw the horizontal lines of best power available together. Where the 2 curves intersect is the equilibrium speed of the ship.



Chapter 9 Practical ship design

Learn to make 'paper doll' boats to evolve your designs. They are fast, cheap, and give great ideas as to what is possible. Later, using the paper doll template as a guide, one can make larger ship models with cardboard, which work great in the engineering competition.



Bow shapes
Stern shapes
Keels/Skegs

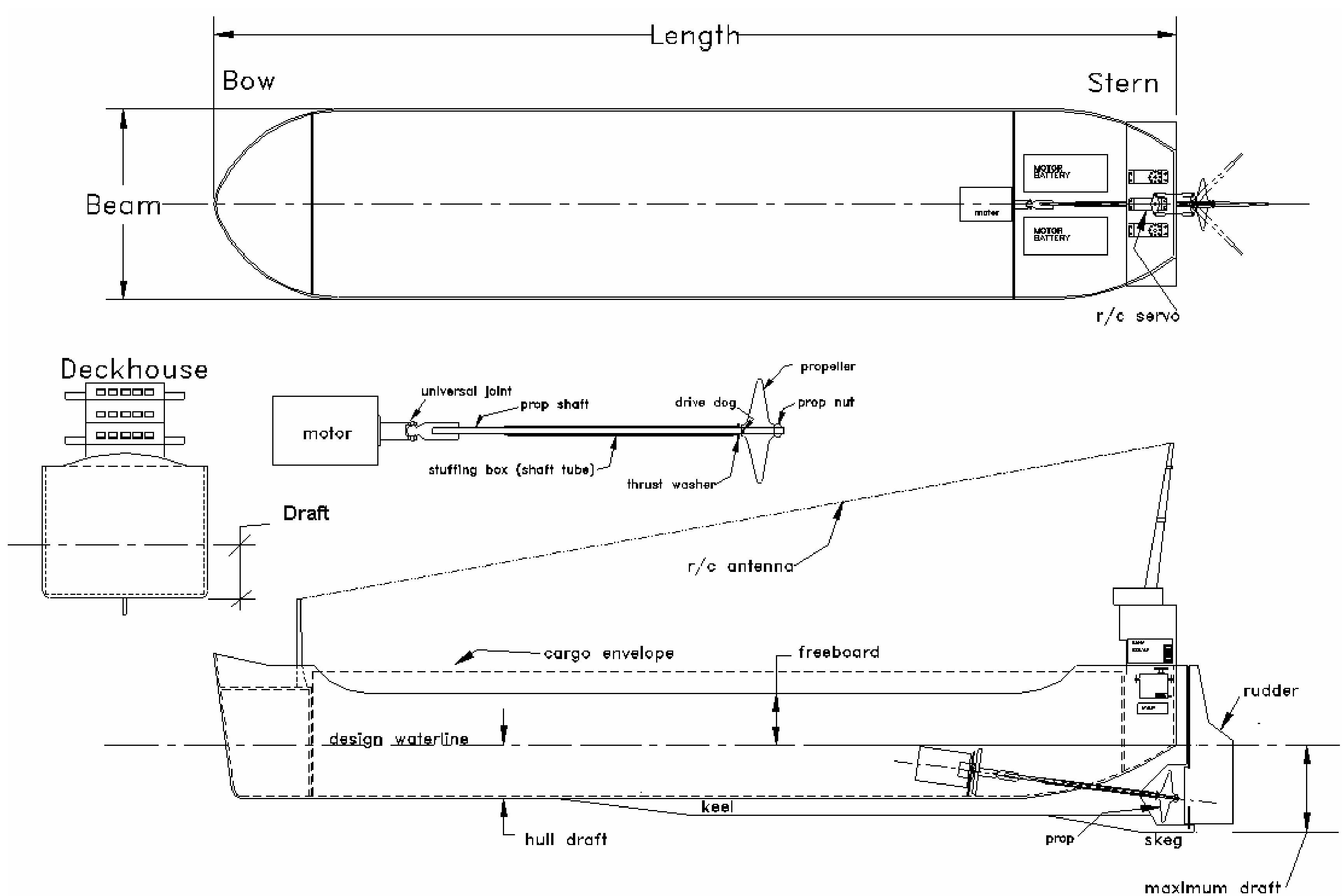
Propeller placement

Propellers need a straight track of water ahead of them in order to maximize the flow thru the disk, so they cannot simply be sticking out of a vertical wall in the water. If you think about it, the water would have to do a major zig-zag to get thru the prop if mounted such. The best place is on the bottom of the hull in clean un-interrupted water, a clean shot in front and a clean shot behind. It needs protecting, so a skeg in front of the prop will keep you from squashing the prop/drive accidentally. If sufficiently away from the ship's back edge, then the hull itself will act as a cavitation plate (won't allow the prop to suck a bubble from the surface into it).

In short, the prop needs a near straight shot of water, needs protection, and must be deep enough in the water or protected by a "roof" (cavitation plate) to keep it free of power-robbing bubbles.

Rudder placement

The rudder needs to be directly in the path of the prop wash, period. If you place the rudder to the side of the prop where it does not get the high speed water flow over it, **you will have nearly no control!** Remember, most of these cargo ship models are pretty slow, and that is the speed of water over your rudder. No speed, no control. But, if you have the rudder in the path of the prop wash just behind the prop, then there is always high-speed water over the rudder, so you will always have control. There should be approximately ¼ of the rudder area ahead of the hinge line (and ¾ behind). This will create a balanced rudder, which will take very little servo force to turn. That's good, considering the little torque available from some of these model car servos. One may make the argument that a rudder in the path of the prop wash (the jet of water blasting out of the prop) will create too much drag. Well…the counter argument is that the rudder can be made much smaller, and it has to be properly streamlined, that is it need an airfoil shape if thick, or just needs to be smooth with rounded edges if it's a flat plate. That's all you need to do.


Length
Bow
Stern
Beam
MOTOR BATTERY
MOTOR BATTERY
r/c servo
Deckhouse
motor
universal joint
prop shaft
drive dog
propeller
prop nut
stuffing box (shaft tube)
thrust washer
Draft
r/c antenna
cargo envelope
freeboard
rudder
design waterline
keel
hull draft
prop
skeg
maximum draft

Chapter 10 Practical Ship Building

Construction materials

Layout tools and methods

Construction methods

Propeller installation (stuffing box, prop shaft, u-joint)

Motor installation (cheater plate)

Rudder installation

Deck house

Paint and finish

Batteries

Use a motorcycle 12V battery if available, or better yet go online to Tower Hobbies or HobbyLobby and for ~ $15 buy a 12V sealed lead-calcium battery that is used for starting glow engines for radio-controlled flying model aircraft (don't forget to buy the charger for it). This should only be used for powering the motor, **NEVER** the radio control receiver!!! The requirements for most radio control receivers are to use a special 4.8V ni-cad battery that you can also find at Tower or HobbyLobby. The 4.8V battery connector is pretty standard among radio control sets. It is also known as a "flight pack", 500maH (milliamp-hours capacity)is sufficiently large.
The motor will need a switch that can take ~ 25 amps, so most motor throttle controllers for model cars will not be able to handle that much current. Again, if you have the money, controllers for radio-controlled brush motors with amperage ratings in the 25-30 amp range can be bought for ~ $ 40, but a simpler solution is at hand. One can use a simple electrical wall light switch from Home Depot for $1.50, and have the servo do a push-pull on the switch that your fingers normally do. Of course, you will only have 1 speed (full) in 1 direction (forward hopefully), but that is all that is required.
Make a set of wire leads with alligator clips on them so that you can easily set up the system, but **don't accidentally cross a positive with ground**, or the resulting spark might take off your finger tip! Always approach the electrical system with caution, because the batteries have a great capacity, even if the voltage is low!

When wiring batteries together (don't if you can help it), wire in parallel (+ with+, - with-) **only** batteries of the same kind, capacity, and voltage. Wire in series (+ to -, + to -) batteries of different voltages to sum their voltage (9.6V + 12V = 21.6V). **NEVER** wire in parallel batteries of different voltages, because the result will be the higher voltage battery will try to charge up the lower voltage battery until the higher voltage has been dumbed-down and the lower voltage has been smartened-up to some kind of an average voltage between the two.

Wiring

Use 14 to 16-gage wire for the connections between the 12V battery and motor. The radio control is of low amperage and comes with it's own wires and connectors. Keep the battery/motor electrical system TOTALLY SEPARATE from the radio control electrical system!

Radio control installation

Keep the receiver wrapped in a plastic bag to prevent ANY water from entering it. The servos for controlling the motor switch and the rudder should be in a separate compartment from the cargo area, and should be well protected from water or accidental bashing. Attach the antenna to a mast for best reception to be free of radio interference. One might also consider putting as large a capacitor across the motor leads (in parallel) to quiet down any interference from motor brush arcing (those blue sparks one can sometimes see on operating motor brushes produce interfering radio noise).

TESTING! TESTING! TESTING!

Chapter 11 Operating the ship

Transportation and safe display of the ship model

Radio control protocols

Stacking the cargo

Driving the course

Chapter 12 Miscellaneous

Writing a technical report

Making drawings