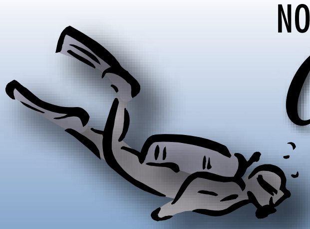
NOAA's
aquarius
America's Innerspace Station



UNCW

Designing an Autonomous Underwater Vehicle (AUV):

Concepts in Lift, Drag, Thrust, Energy, Power, Mass, and Buoyancy

Focus

Engineering principles behind the design of underwater robots, and how they relate to locomotion in aquatic animals like fishes, sea turtles, and whales.

Grade Level

9-12 (Physical Science)

Focus Questions

How do Newton's laws affect the performance of an autonomous underwater vehicle (AUV)?

How are the concepts of mass, buoyancy, potential energy, kinetic energy, and power related to the performance of an AUV?

Learning Objectives

Students will construct a model of an Autonomous Underwater Vehicle (AUV).

Students will be able to explain how drag, thrust, and lift forces affect the performance of their model AUV.

Students will be able to explain how their AUV can be designed to optimize drag, thrust, and lift forces.

Students will be able to compare and contrast the locomotion of AUVs and aquatic organisms like fishes, sea turtles, or whales.

Students will be able to explain the difference between mass and buoyancy of an object immersed in water, and explain why AUVs and aquatic organisms need to adjust their buoyancy.

Students will be able to explain how potential energy turned into kinetic energy in real AUVs, the AUV model, and swimming organisms.

Students will be able to compute energy and power released during a swim.

Materials (per AUV)

- 1 - soft drink bottle (any size, but 20 fl. oz works well)
- 2 - 3 strong rubber bands (long enough to be stretched the length of the bottle without breaking)
- Small piece of plastic to make fins (cut up a Tupperware container or plastic gallon milk jug)
- 4 - 6 metal washers of various sizes (approximately 7/8" diameter with hole diameter 3/8"), available at any hardware store
- Hot glue gun and glue sticks, enough for students to share when making AUVs
- Propeller of some kind (from a toy boat, aircraft, or hobby shop)
- Exacto knife
- Drill and drill bits
- Stopwatch (one per student AUV)
- Pool or long plastic tub with water for testing AUV designs, at least 10 inches deep
- Copies of "Constructing a Model AUV" and "Student Question Sheet," one for each student group
- (Optional) - Overhead transparencies for Figures 1-3, 5-7

AV Equipment

- None, unless overhead transparencies are made for Figures 1-3, 5-7

Teaching Time

Three 45-minute class periods

Seating Arrangement

Groups of 2 - 4

Key Words

Laws of physics
Drag
Lift
Thrust
Buoyancy
Weight
Viscosity
Robotics
Energy
Power
Autonomous underwater vehicle (AUV)
Aquatic locomotion

Background Information

Aquarius is an undersea laboratory owned by the National Oceanic and Atmospheric Administration (NOAA). Its purpose is to support research on oceans and coastal resources by allowing scientists to live and work on the seafloor for extended periods of time. *Aquarius* is presently deployed three and a half miles offshore in the Florida Keys National Marine Sanctuary. It operates 62 feet beneath the surface at Conch Reef. Missions typically last 10 days and aquanaut candidates undergo five days of specialized training before each mission starts. Visit http://www.uncw.edu/aquarius/ for more information, including a virtual tour of the *Aquarius* laboratory.

Aquarius missions are focused on understanding our changing ocean and the condition of coral reefs. Coral reefs are threatened locally, regionally, and globally by increasing amounts of pollution, over-harvesting of fisheries, disease, and climate change. Like the Florida National Marine Sanctuary, all National Marine Sanctuaries (Sanctuaries) are recognized as important management tools for marine conservation, and provide information that can be used to help dwindling fish populations, conserve critical habitats and biodiversity, and help scientists manage sites to avoid conflicts among fishers, boaters, and divers. Effective design and management of the Florida National Marine Sanctuary to protect coral reefs requires specific information on the complex ecosystems typically associated with the reefs, particularly fish populations. In recent years, visual censuses by SCUBA divers have become increasingly important to marine conservation programs. In addition to research conducted by professional scientists, many fish population surveys are also done by volunteers. The Reef Environmental Education Foundation's Fish Survey Project, for example, allows volunteer SCUBA divers and snorkelers to collect and report information on marine fish populations. The data are collected using a standardized method, and are archived in a publicly-accessible database on REEF's Web site (http://www.reef.org).

Autonomous Underwater Vehicles (AUVs) (Figure 1) are swimming robots that gather data in three dimensions from the underwater world, meaning they have the ability to simultaneously measure many parameters in the habitat they are swimming through, painting a realistic picture of the natural environment. This helps marine scientists to understand the ocean in new ways. For example, an AUV can use sonar to count fishes within a certain three-dimensional range, and at the same time measure the quality of the water in which the fishes live. The older method of gathering the same data would be to tow a net through the water from a boat, haul the net on board, and then count the fishes that were not fast enough to avoid being caught by the net. Additional instruments were then lowered over the side of the boat to measure the water quality. Clearly, an AUV can gather more precise data more quickly and less expensively than older methods and technologies.

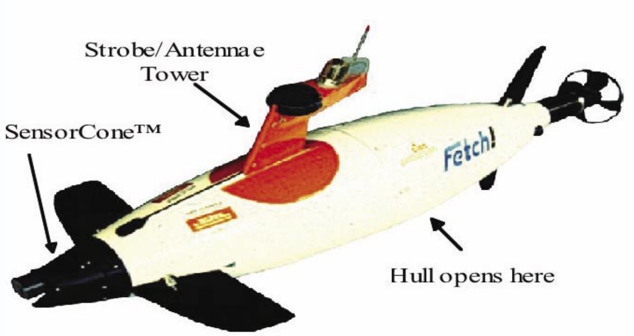


Fig. 1. Fetch! ®, an Autonomous Underwater Vehicle. Length 2 m. Weight 80 kg.

In 2002, an AUV known as "Fetch" was used at the *Aquarius* site to gather data on the oxygen concentration and pH of the water around the reef. These snapshots of data allowed scientists to determine how photosynthesis, respiration, and weather affect how much oxygen there is on the reef over the course of a day or a season. The AUV must swim complex patterns around the reef (see Figure 2) to gather underwater data to describe variations in oxygen and pH conditions (see Figure 3).

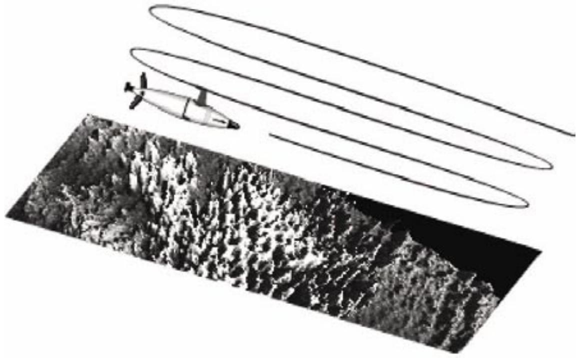


Fig. 2. AUV swimming a lawnmower pattern over a reef (shown as a side scan sonar image).

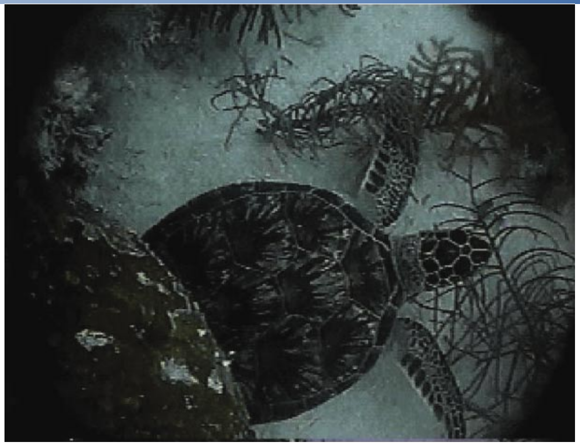


Fig. 3. Underwater video image of sea turtle, coral head, and gorgonians gathered near the NOAA NURP *Aquarius* underwater habitat in Key Largo, by the Fetch AUV flying at a constant altitude.

Like a fish or whale, for an AUV to swim it must obey the laws of physics, and the peculiarities of moving through a fluid to make its way through the ocean. This activity will guide students through construction of and experimentation with a model AUV. Through their experiments, students will explore important physics concepts that affect aquatic locomotion.

Learning Procedure

1. Briefly review Background Information on the *Aquarius* habitat, coral reefs, and ways in which these reefs are threatened (http://www.uncw.edu/aquarius and http://www.nos.noaa.gov/education/welcome.html provide "one-stop shopping" for this review).

2. Review Newton's laws of motion:

   Law #1: An object at rest stays at rest, and an object in motion stays in motion at the same speed, only if all the forces acting on it cancel each other out.

   Law #2: Force = Mass x Acceleration. If using MKS (meters, kilograms, seconds) units, force comes out in Newtons (N).

Law #3: For every action (application of force), there is an equal and opposite reaction (application of force in the opposite direction).

In the context of an AUV, Law #1 means that swimming objects, like a robot maintaining constant speed, must have all their forces balanced so they cancel out. Newton discovered it takes a force imbalance to change an object's speed or direction.

Law #2 shows us where force comes from. This equation can be rewritten as:

Acceleration = Force/Mass

Ask the following question: "If an object is moving through water, what two things could be changed to cause the object to accelerate (speed up)?" Students should recognize that increasing the force generated against the water or decreasing the mass of the object would cause the object to accelerate. Fish, whales, and AUVs need to generate force in order to accelerate. They do this by pushing on the water with a fin or a propeller. They do not change their masses. If the same force is generated by two swimming objects, the object with the smaller mass will accelerate faster.

Law #3 is demonstrated when you push down on a desk with your finger: the desk pushes back with an equal and opposite force. When a spinning prop or the tail of a fish pushes against some water, the water pushes back. The only difference is that since water is a liquid, it flows as it pushes back (it does not hold its shape like the desk, a solid, does).

If an object is accelerating, there must be a net force acting on the object. If an object's acceleration is zero, the net force acting on it is zero! This is clear using the equation above.

The forces acting on a swimming object, like the whale shown below in Figure 4, are thrust, drag, buoyant force, weight, and lift. The arrows represent forces. The length of the arrow represents the strength of the force. A similar illustration of an aquatic swimmer could illustrate these concepts.

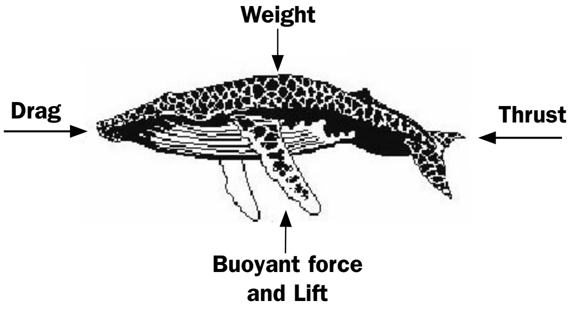


Fig. 4. Forces acting on a whale during swimming. Have students draw a similar diagram for their AUV models after they have made it and had a chance to operate it.

We give these forces names to help us remember what they do to a swimming object. Thrust is a force that moves an object through the water. Drag is a force resisting the movement of the object through the water. The concept of drag has puzzled scientists for centuries, and it may still be puzzling by the end of this lab, but students will experience its effects by making and experimenting with their own AUV models. For now, suffice it to say that drag arises from the viscosity of the water as it passes in close proximity to the skin of the swimming object. Buoyant force arises from the water displaced by the object. The weight of the object is the force caused by the gravitational attraction between the Earth and the object. Lift is a force that arises in a manner similar to drag, but it is directed upward. With an

AUV, a fish, or a whale, lift can arise as seawater flows over structures like fins. Students may be more familiar with this from an aeronautics perspective.

Ask students to consider the following question: If an object swimming in water is traveling at constant speed and constant depth, what must be true about the balance between drag, thrust, buoyant force, lift, and weight? Students should realize that

- Drag = Thrust, and
- Buoyant force + Lift = Weight

The purpose of this activity is to allow students to design a model of an AUV that swims at constant speed and depth underwater, and to see how modifications to their design affect its swimming performance.

3. Have each student group construct and test a model AUV as directed on the "Constructing a Model AUV" sheet, and complete the "Student Question Sheet." You may also want to have students submit a labeled force diagram for their AUV model in level flight at constant speed. Have them do the same for their AUV model, shortly after release and just before it stops moving.

   Question #3 on the Student Answer Sheet is a good test of students' understanding of Newton's laws and their ability to apply these laws to explain why their model veers. Students should realize that if their model veers, there must be force pulling sideways on the model, affecting the direction of its motion.

4. (Optional) For more advanced students, refer back to Figure 2 and try the computations in "What a Drag!"

5. Have the students give a short presentation on how they modified their designs to decrease drag, alter buoyancy, etc. Based on their observations with their own models, have students brainstorm suggestions for improving the hydrodynamic design of the real Fetch AUV, and submit notes and sketches.

The BRIDGE Connection

www.vims.edu/bridge/index_0400.html – April 2000 Data Tip, with information and student activities focused on underwater technology.

The "Me" Connection

Have students write an essay describing how they might use a moving robot to help complete a task that they routinely perform, and how Newton's Laws would affect the performance of this robot.

Connections to Other Subjects

English/Language Arts, Mathematics, Earth Science, Chemistry

Evaluation

"Student Question Sheets" completed in Step #3 and presentations in Step #5 provide opportunities for assessment.

Extensions

For those students who have explored the concept of drag through "What a Drag!": Have students time the motion of their AUV through the water over a known distance with a stopwatch to get a speed estimate. Ask them what they need to compute the drag coefficient of their model. Answer: they need to measure the thrust (force) produced, which is equal to the drag when the vehicle is swimming at constant speed. They also need to estimate the surface area of the model. One way to try measuring force in the pool is to hook the AUV up to a sensitive spring scale via a fishing line with a snap swivel (available at hardware or tackle shop) and read the force produced as the AUV swims in place. If they measure F (force or thrust) and V (swimming velocity), estimate S (surface area of the object), and look up rho (density of the water), then they can compute Cd (drag coefficient; depends on the shape of the object and has no dimensions; it is a pure number). Remember to keep everything in MKS units to make the answer correct. In other words, speed should be converted to m/s, density of the water needs to be in kg/m^3 (about 1000 for water), the surface area of the model needs to be in m^2, and the force on the spring scale needs to be converted to Newtons. Then Cd will come out to its correct dimensionless value. Drag coefficients will likely range anywhere from 0.05 to 0.2 depending on their design. A very streamlined shape, like a tuna, would have a value well below 0.01.

Resources

www.spiauv.com – Web site for FETCH, the AUV designed by Dr. Mark Patterson and his colleague Jim Sias.

www.nurp.noaa.gov/robots.html – Web site of the National Undersea Research Program

adcp.whoi.edu/REMUS – Web site for Woods Hole Oceanographic Institution's Remote Environmental Monitoring Unit S.

National Science Education Standards

Content Standard A: Science as Inquiry

- Ability to do scientific inquiry
- Understanding scientific inquiry

Content Standard B: Physical Science

- Motions and forces
- Transfer of energy

Content Standard E: Science and Technology

- Abilities of technological design
- Understandings about science and technology

Content Standard F: Science in Personal and Social Perspectives

- Science and technology in local, national and global challenges

Content Standard G: History and Nature of Science

- Science as a human endeavor
- Nature of scientific knowledge

National Council of Teachers of Mathematics Standards

(Note: These are primarily for those students completing computations in the "What a Drag!" section of the activity)

Algebra

- Represent and analyze mathematical situations and structures using algebraic symbols
- Use mathematical models to represent and understand quantitative relationships

Measurement

- Understand measurable attributes of objects and the units, systems, and processes of measurement
- Apply appropriate techniques, tools, and formulas to determine measurements

Problem Solving

- Solve problems that arise in mathematics and in other contexts
- Apply and adapt a variety of appropriate strategies to solve problems

Connections

- Recognize and apply mathematics in contexts outside of mathematics

Representation

- Select, apply, and translate among mathematical representations to solve problems

Activity developed by Dr. Mark Patterson, Virginia Institute of Marine Science (VIMS) Scientist; Ms. Susan Haynes, Marine Education Specialist (VIMS); and Lawrence Carpenter, Graduate Student at (VIMS)

Student Handout

Constructing a Model AUV

1. Drill a loose hole in the bottom of the bottle large enough for the propeller shaft to fit through. The bottle is the body of the model AUV (Figure 5).


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Fig. 5. AUV model made from pop bottle, toy propeller, and rubber bands. White wings are fins that stabilize the model and keep it from rotating as it swims. Designed by Dr. Patterson's graduate student, Lawrence Carpenter.

2. Insert the propeller (thrust generator) and several elastic bands (power source) through a few washers (Figure 6).


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Fig. 6. Detail of toy prop. We removed the ring that connected the blade tops, using a pair of scissors. Note the washers on the end, which served as bearings (and affect the buoyancy), and the rubber bands tied to the end of the prop shaft that came off the toy.

3. Pull the bands through the bottle using a paper clip or coat hanger that has been straightened out, and screw the bottle top down on them to hold them in place. OPTION: Cut two small slits in the neck of the bottle under the cap (not shown) and slide the rubber bands into the notches. This will keep the rubber bands from flying back down the bottle if it is necessary to unscrew the cap to adjust the buoyancy or to change the configuration of your model.

4. Cut two fins out of a plastic milk jug or Tupperware container. Seal to each side of the bottle with hot glue (Figure 7).


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Fig. 7. Close-up of bead of hot melt glue used to attach plastic fins to plastic bottle. Put bead(s) along both sides of fins to increase ruggedness.

5. Once your model is constructed, it's time to test it out. Testing works best in a pool, but a long plastic tub will suffice. Remember your goal is to see how modifications to your design affect the swimming performance of your AUV. Try to get your model to swim at a constant speed and a constant depth for a select amount of time (try 5 seconds) and observe how it behaves.

6. Once the model has been tested once and observations have been made, answer the questions on the Student Question Sheet. Make modifications to your model as necessary. For example, some modifications were needed in order to get the model shown in Fig. 5 to swim horizontally. We added a couple of teaspoons of air, and taped four washers to the bottle cap (not shown).

Student Handout

Student Question Sheet

1. Too much /too little weight (# of washers) or too much/too little air trapped in the bottle will affect the way your AUV moves. An imbalance in weight and/or air may make your model come to the surface or hit the bottom. What did you do to balance these forces in order for it to swim horizontally? Explain why your model worked or did not work.

2. How far does your model swim? Does the number of times you pre-wound the rubber bands with the prop affect the distance your AUV travels? How is energy stored in the rubber bands? How is the stored energy released to make the prop move?

3. Does your model go straight, or have a tendency to veer? If the latter, what is causing the veering? How might you fix the veering? How do fish veer when they need to?

Student Handout

4. What if you make the nose of the AUV model more streamlined? Will your model swim farther for the same number of twists of the rubber band? Can we learn something from the shapes of fishes and dolphins and whales? (Modeling clay can be used here to quickly alter the shape of the model. If the model becomes negatively buoyant, simply put more air into the bottle.)

Student Handout

What a Drag!

Let's explore drag reduction, and the relationship to energy and power. The application of force through a distance is energy (Force x Distance = Energy). The rate at which you spend energy is power (Energy/Time). All things that swim through the water must cope with hydrodynamic drag. Drag reduction is a field of engineering that is very active and important to modern society. Small improvements in drag reduction can result in substantial economic savings to people in the shipping industry who have to pay money to move things through air and water. Aquatic animals must pay to move through the water using energy stored in the food they eat. The more efficiently they move through the water, the less energy they need. Or, put another way, the more energy they will have for other activities like growing or reproducing. Not surprisingly, AUV designers want drag to be low, too. The lower the drag, the farther an AUV can swim on its batteries.

Drag is affected by the size, shape, and speed at which the object is moving through air or water. Here is an equation to compute drag:

Force due to Drag = 0.5 rho V^2 Cd S, where rho = density of the water, V = the swimming velocity, Cd = drag coefficient (depends on the shape of the object), and S = the surface area of the object. Cd has no dimensions; it is a pure number.

Streamlined objects like fish or well-designed AUVs have low values of Cd, compared to non-streamlined shapes. Note that the drag goes up as the square of the swimming speed. So if an animal or AUV wants to swim a little bit faster, it will have to generate a lot more thrust to overcome drag. This sort of parabolic relationship is a real constraint on aquatic locomotion.

Swimming animals and AUVs can reduce drag by swimming slower, or reducing Cd (by changing their shape), or reducing the surface area in contact with the water (through changes in size and/or shape.)

What happens if we know the drag of an object and multiply it by the distance it swims? Drag Force x Distance = Energy. The further an AUV swims, the more energy it uses. The faster it swims, the greater force it will need to generate, and again it will use more energy than swimming at a slower speed.

What happens if we know the drag of an object and multiply it by the speed at which it swims? Force x Distance/Time = Power. Remember that at constant swimming speed, Drag = Thrust, and Drag is proportional to Velocity^2. But Distance/Time = Velocity, so Power is proportional to Velocity^3. So a small increase in swimming speed leads to a very big increase in the energy used per unit time (the power), because of the cubic relationship between power and speed.

Experimenting with your model, you can explore methods for reducing drag, and hence the power your AUV must expend to swim.