Chapter 2

Vehicle Design, Construction, and Operation

2.1 Introduction

This chapter describes the design of the vehicle and provides a detailed description of the construction and operation. Section 2.2 is broken up into three parts. Section 2.2.1 provides a breakdown of the vehicle into two categories: the vehicle structural components and the electrical components that are internal to the vehicle. Section 2.2.2 gives a detailed description of the mechanism that allows the vehicle to produce both a steady and unsteady jet with the same mechanical efficiency. The final section, section 2.2.3, outlines the operational components that are external to the vehicle.

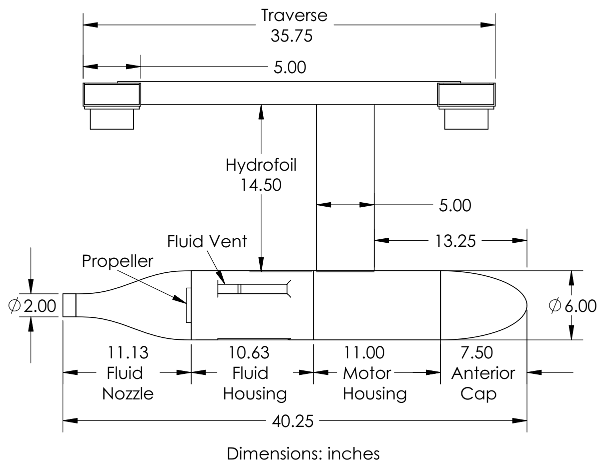
2.2 Detailed Description of Vehicle Design and Construction

2.2.1 Vehicle Components

For this study, a self-propelled underwater vehicle was designed and developed capable of producing both a steady and unsteady jet while maintaining the same η_{mech}. The vehicle's physical attributes resemble that of a submarine.

2.2.1.1 Mechanical Components

The design and detailed drawings of the submarine parts were developed using the 3D CAD product design engineering software, SolidWorks. The manufacturing and construction of the submarine shell was performed by David Merriman of D and E Miniatures. The exterior structure of the submarine is composed of four main parts: water filled anterior cap, motor housing, fluid housing with attached hydrofoil and the fluid nozzle as illustrated in figure 2.1. Each part was made from a composite glass-reinforced plastic, and has a 0.13-inch wall thickness. When fully assembled, the submarine is 40.0 inches in length and 6.0 inches in nominal diameter. Figure 2.1 shows a schematic and image of the fully assembled vehicle that has been designed for this project.



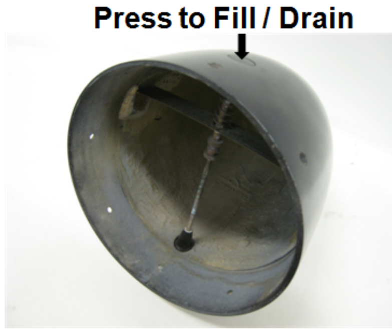
(a) SolidWorks drawing of vehicle components with attached traverse.

(b) Image of vehicle shown with length scale reference.

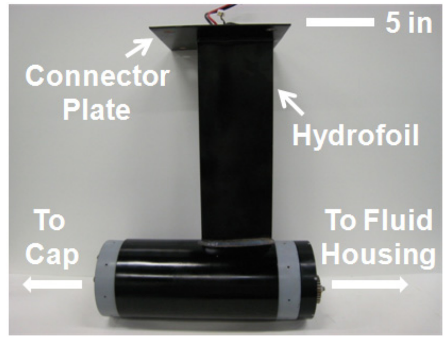
Figure 2.1. Schematic and image of the fully assembled vehicle.

The anterior cap of the submarine was designed to minimize frontal drag by using an elliptical shape. The cap has a cross-sectional diameter of 6.0 inches and an overall length of 7.5 inches. The submarine was designed to be neutrally buoyant, therefore, located on top of the cap is a button that once pressed allows water to enter and fill the cap. Figure 2.2(a) shows an image of the filling mechanism. The anterior cap of the submarine is attached to the motor housing of the submarine using 8 (6-32 thread, 5/16 inch length) equally spaced screws.

The motor housing component of the submarine is a watertight cylinder that contains the sub-



(a) Image of the filling/draining mechanism.



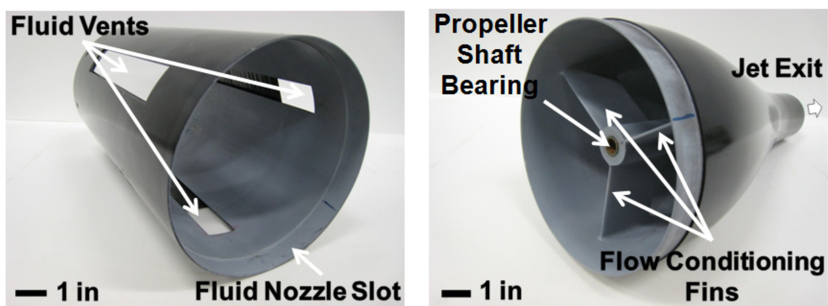
(b) Image of the submarine motor housing with attached hydrofoil and connector plate.

Figure 2.2. Image of the anterior cap and the motor housing of the vehicle.

marine motor and tachometer. The length of the motor housing is 11.0 inches and it is 6.0 inches in diameter. Fused to the body of the housing via epoxy and fiberglass is a hydrofoil. When assembled, the hydrofoil is positioned 0.25 inches away from the seam of the mating location between the motor and fluid housing. The hydrofoil provides the submarine with the stability to travel in a unidirectional path down the flume facility while providing a smaller wake disturbance in comparison to other geometries. The shape of the hydrofoil was inspired by a NACA 0024 airfoil. The hydrofoil has a 5.1-inch chord and is 14.5 inches in length. Its geometry was modified such that the thickness of the hydrofoil was twice that of the NACA 0024 airfoil. This increase in thickness provided increased strength and size to the hydrofoil, allowing for the passage of a steel cylindrical pipe. This increase in the thickness of the hydrofoil increases flow separation at high vehicle speeds (35 to 56 cm/s) but was necessary to provide structural strength to the vehicle. Analysis of jet dynamics was avoided in the area directly behind the hydrofoil. The pipe channels electrical wiring from the surface to the core of the submarine. The steel pipe was welded to a 0.4-inch-thick, 6.5-squared-inch steel plate. The steel connector plate mounts the submarine to a traverse. Figure 2.2(b) shows an image of the core of the submarine with attached hydrofoil and connector plate.

The fluid housing is attached to the backside of the motor housing using 8 (6-32 thread, 5/16 inch length) equally spaced screws. The fluid housing is 6.0 inches in diameter and 10.6 inches in length. Fluid has the ability to enter 3 equally spaced rectangular slots. The slots are 6.0 inches long, 1.0 inch wide and are positioned axially in the center of the fluid housing. The slot areas were later modified to produce a pulsed jet with vortex ring formation as discussed in section 4.3. Figure 2.3(a) shows an image of the fluid housing.

After fluid enters the fluid housing, it passes through a propeller into the fluid nozzle. The propeller is situated at the intersection of the fluid housing and nozzle. It is a 3-inch, 7 skewed blade brass propeller (Ships n' Things, Manville, New Jersey). The final selection of the propeller was based on availability and evaluated performance. Various other propellers were tested but proved insufficient to provide the thrust necessary to propel the submarine. The final propeller is shown in figure 2.7.



(a) Image of the fluid housing with visible partial blockage of two of the fluid slots.

(b) Image of the inside of the fluid nozzle component.

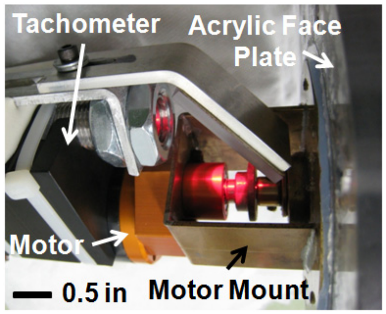
Figure 2.3. Upstream image of the fluid housing and the fluid nozzle components.

The fluid nozzle is press fit into the fluid housing. It is secured with electrical tape wrapped along the seam. The shape of the fluid nozzle is contracted from a diameter of 6 inches to a diameter of 2 inches using a 6th-order polynomial curve fit to provide smooth, attached flow at the exit of the nozzle. The length of the nozzle is 11.13 inches. The fluid nozzle also provides support to the propeller. Given that the propeller shaft extends slightly beyond the length of the fluid housing, this support is necessary to dampen vibrations induced by the propeller rotation. The end of the propeller shaft sits in a Oilite bearing that is supported by 3 vertical fins. See figure 2.3(b). These fins also provide flow conditioning by breaking up large eddies in the propeller wake.

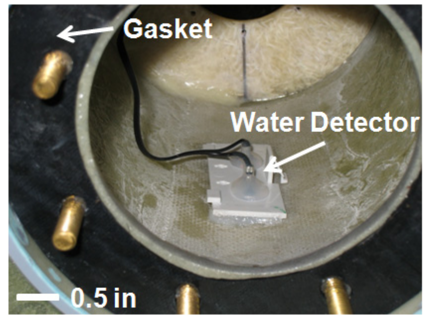
The submarine is mounted to a traverse by securing four 7/16 inch screws to the center beam of the traverse. The traverse is an I-beam configuration manufactured from $2.0 \times 5.0 \times 0.125$ inch anodized aluminum rectangular tubing. To protect the surface of the aluminum from oxidation, the parts were anodized. The total length of the traverse spans 35.75 inches and is 54 inches in width. Rectangular holes were cut as necessary along the members of the I-beam to minimize weight. The submarine must not only propel itself but also pull the traverse which rests on four low-friction roller-bearing pillow blocks (Lee Linear) which have a low rolling dynamic coefficient of friction, 0.004 on average, and low resistance to motion. Two of the pillow block bearings are rigidly fixed to the traverse using 4 screws (1/4-20 thread, 0.75 inch length) which connect to a 0.25-inch square plate and then into the traverse. The pillow block bearings on the opposing side are allowed to slide laterally. These two pillow blocks are connected with 4 (1/4-20 thread, 0.75-inch length) screws to a connector plate which is connected to the traverse by a pin which rests in a slot. In figure 2.1(b), the traverse and pillow blocks are partially visible on the top left of the image.

2.2.1.2 Internal Electrical Components

The submarine is powered by a 2 hp motor (AstroFlight Cobalt 60). It contains a superbox that allows for a 2.7 to 1 gear ratio. The voltage range for this motor is 24 to 36 V and supports a maximum continuous current of 35 A. The motor is mounted to an acrylic faceplate. This faceplate creates a watertight seal for the motor housing of the submarine. As the motor rotates, a tachometer (Monarch Instruments) that is mounted to the motor measures the motor rpm using a remote optical sensor (ROS), see figure 2.4(a). The sensor requires 3 to 15 VDC at 40 mA. The ROS is capable of detecting a reflected pulse from a reflective tape covered target at distances up to 36 inches. It produces a negative TTL pulse, from 5 to 0 V as it detects a reflection from the tape. A water detector (Watchdog) is included in the motor housing for safety reasons and is powered by a 9 V battery. The sensor is located at the bottom of the core and shown in figure 2.4(b). A continuous alarm sounds once water comes in contact with the sensor. The alarm is deactivated by allowing the sensor to dry or disconnecting power to the sensor.



(a) Image of motor mount with attached tachometer.

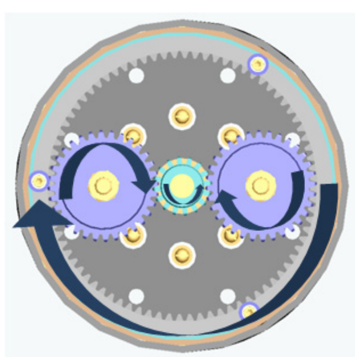


(b) Image of water detector mounted at the bottom of the core of the vehicle with the motor removed.

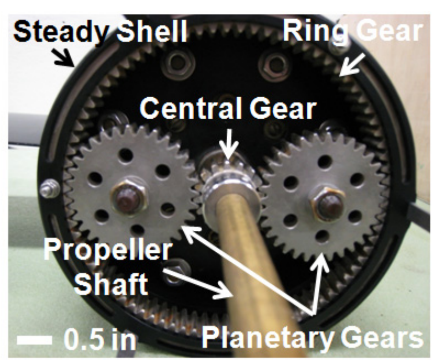
Figure 2.4. Images of electrical components internal to the vehicle.

2.2.2 Description of Jet Mechanism

The submarine is capable of producing both a steady and unsteady jet with the same η_{mech} by maintaining the same load on the motor in each case. Located inside of the fluid housing is a rotating cylindrical shell. Changing the geometry of this shell allows both modes of propulsion to be produced. These shells rotate through a series of gears (Stock Drive Products/Sterling Instruments) that are connected to the motor shaft. The rotation of the shell is geared down by a ratio of 5. The reduction of the rotational speed of the shell was limited by the size of the inner diameter of the fluid housing and the availability of gears. The gearing mechanism consists of 4 gears; a central gear which is directly connected to the motor shaft, 2 planatery gears, and one ring gear, see figure 2.5.



(a) Schematic illustrating gear rotation.



(b) Image of gearing mechanism used to generate both steady and unsteady jet propulsion.

Figure 2.5. Gearing mechanism used to generate both steady and unsteady jet propulsion.

The central gear and planatery gears are stainless steel, and the ring gear is composed of carbon steel. The surface of the ring gear was nickel plated to prevent oxidation. The bore diameter of the central gear was increased from 0.315 to 0.438 inches in order to fit the shaft diameter of the propeller. The two planatery gears are mounted to a face plate using a stainless steel shoulder screw (10 mm shoulder diameter, 25 mm shaft length, M8 thread) which is directly mounted to the motor housing by fastening eight 1/4-20 screws which pass through the face of the submarine core. These screws are permanently set in the core of the submarine with epoxy. The planetary gears were modified by drilling six 0.25-inch diameter through holes in a circle pattern and also cutting a pocket on the inner face of the gear to decrease gear weight. To decrease the friction of the rotating planetary gears, two $10 \times 22 \times 6$ mm shielded stainless steel ball bearings are used. One bearing is mounted on the inside of the face plate and the other is located in the pocket of the gear. The ring gear, which is driven by the planetary gears, is attached to the shell using three M3, 35 mm length socket head cap screws. A total of six $3 \times 10 \times 4$ mm shielded stainless steel bearings are used in supporting the shell rotation inside of the fluid housing. Three bearings are mounted on the ring using the three M3, 35 mm socket head cap screws. The remaining three are mounted on the opposite thin ring using three M3, 18 mm socket head cap screws. The bearings rotate in this ring as the shell rotates. Figure 2.8(a) shows two of the bearing that rotate in the ring along with one of the bearings that is mounted to the ring gear. The thin ring is held in place by fluid housing supports.

2.2.2.1 Unsteady Jet Configuration

The unsteadiness of the jet efflux is generated by the inner rotating cylindrical shell, or flow chopper, and is geared to the primary propeller and rotates between 0 and 13 Hz. Figure 2.6 illustrates the operation. In a pulsed jet configuration, the fluid inlets are periodically blocked by a cylindrical shell that rotates inside the hull of the vehicle. This periodic blockage of the flow inlets results in a pulsed flow at the nozzle outlet. The frequency and amplitude of the pulsing is controlled by the frequency of the inner shell rotation and by the fraction of the fluid inlets that are blocked by the flow chopper. A small downstream portion of the fluid inlets, 1 inch by 11/16 inches cross-sectional area, remains open to avoid cavitation within the nozzle due to the transient pressure drop that occurs as the inlets are blocked.

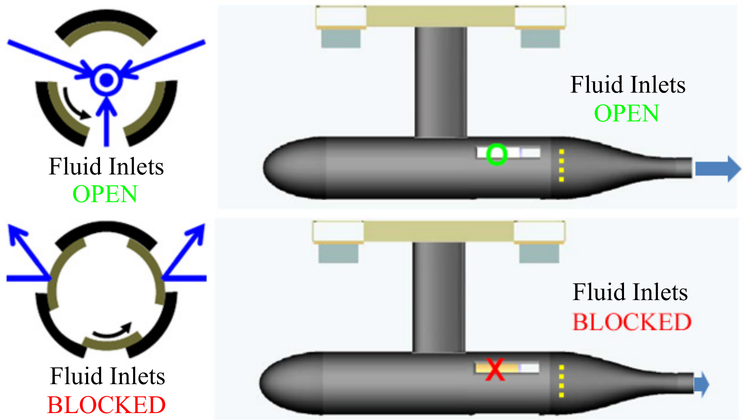
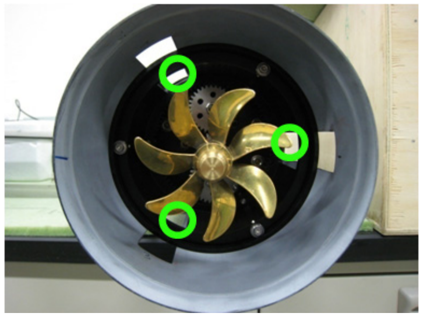


Figure 2.6. Principle of operation for pulsed jet configuration. Black arrows in left panels indicate inner shell rotation.

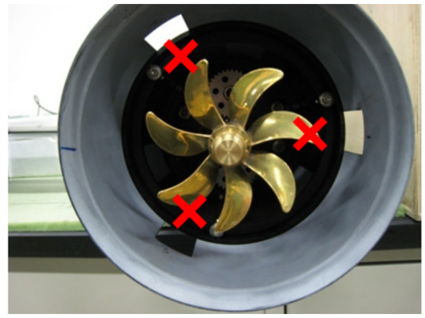
Figure 2.7 shows an upstream view of the unsteady rotating shell mounted inside the vehicle. The open and blocked orientations of the inner shell are shown in the left and right panels respectively. The planetary gear system, used to control the rotational speed of the shell relative to the rotation speed of the propeller, can be seen in the background. The always-open downstream portion of the fluid inlets is visible in the foreground. The unsteady shell shown in this figure was later redesigned to decrease the frequency of pulsing in order to produce a pulsed jet with vortex ring formation (section 4.3.1). The final design of the unsteady shell geometry was manufactured from a solid piece of aluminum, see figure 2.8(a). In this figure, the unsteady shell is attached to the ring gear. To maintain a constant moment of inertia, two stainless steel counterweights were placed in opposition to the fluid blocker.

2.2.2.2 Steady Jet Configuration

The only difference in the mechanical design of the steady and pulsed jet versions of the propulsion system is in the solidity of the inner rotating shell. The steady shell was designed to have the same moment of inertia of 4.59 kg cm^2 as the unsteady shell. The steady shell design consists of 5 parts;



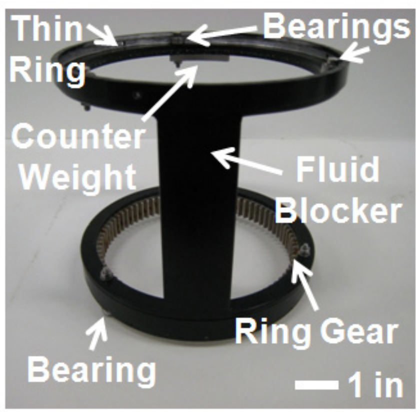
(a) Flow chopping mechanism in an open configuration as denoted by the green circles.



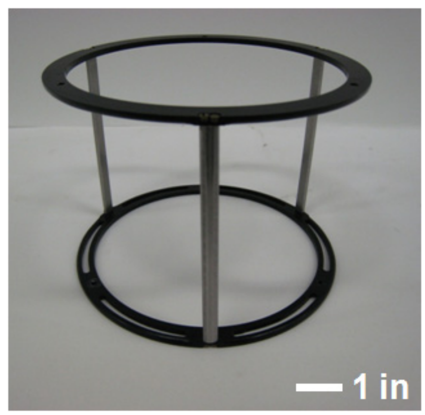
(b) Flow chopping mechanism in a closed configuration as indicated by the red x's, the secondary vents remain open.

Figure 2.7. Image of the upstream view of the unsteady rotating shell mounted inside the vehicle with the nozzle removed.

3 thin stainless steel ribs and 2 aluminum rings as shown in figure 2.8(b).



(a) Image of the inner rotating shell for the pulsed jet with attached ring gear.



(b) Image of the inner rotating shell for the steady jet.

Figure 2.8. Images of inner rotating shells for both pulsed jet and steady jet vehicle configurations.

This design feature is intentional to maintain identical mechanical efficiency for both steady and pulsed jet configurations. As shown in figure 2.9, the steady jet system uses a rotating inner shell whose blockage is negligible for any azimuthal position of the shell. The output jet efflux is nominally steady.

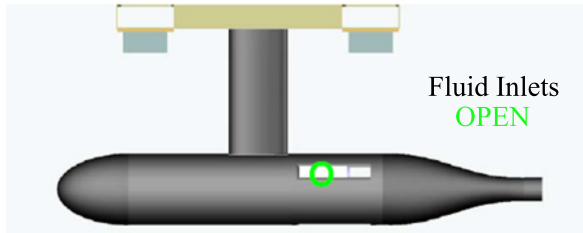


Figure 2.9. Principle of operation for steady jet configuration.

2.2.3 Vehicle Operation

The submarine throttle is controlled by a speed controller (Astro Flight Incorporated) connected to the motor. The voltage range for this controller is 7 to 60 V with a continuous current rating of 60 A. Power is transmitted to the speed controller through a 12-gauge, 25 m long power cable connected to the electrical box stationed on a work table in the center of the testing area. Provided that the electrical box is located in the center of the testing area, a 25 m long power cable is sufficient to allow the submarine to move down the 30 m long testing area. The motor current passes through a 0.01 Ω shunt placed in series on the negative voltage line and located within the electrical box. This shunt is used to measure system current. A power switch is located on the outside of the electrical box which allows opening and closing of the motor power circuit.

Initial experiments were conducted using three 12 V, 7 Ah rechargeable batteries. An Agilent 6674A power supply with a capability to supply 0–60 V at 0–35 A later replaced the batteries. As a safety precaution, a 35 A fuse was placed in series between the speed controller and power supply. Typically during self propulsion, the submarine draws 12 A at 37 V. Communication to the speed controller is achieved through an RF receiver (Polk's Hobby Seeker 6). The wiring diagram is shown in figure 2.10.

The Seeker 6 operates at a 75 MHz frequency and is a six-channel receiver that can be used with any FM transmitter using any of the 50 channels within the 75 MHz aircraft frequency. Only one channel is used to control the throttle of the vehicle. The FM transmitter used in conjunction with the receiver is a Polk's Hobby Tracker III.

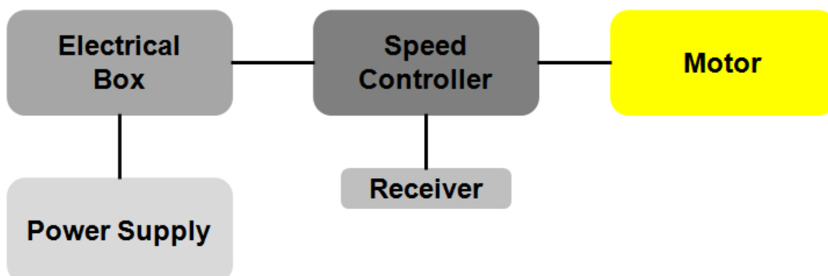


Figure 2.10. Schematic of electrical wiring necessary for the operation of the vehicle.