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Development and Testing of an Underwater Scooter Model

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Abstract. A diver propulsion vehicle (DPV) is a device used by scuba divers to help pull them through the ocean without the use of additional exertion. The objective of this research project was to build a diver propulsion vehicle (DPV), or underwater scooter as it came to be known. The scooter would have to reliably pull an adult through water and allow neutral buoyancy whereby the user would neither submerge to the bottom nor float to the surface. The entire system would also need to be waterproof to protect the electronics and sustain the life of the scooter. The prototype also had to be durable and able to function for an extended period of time. Finally, the scooter had to be built at a relatively low cost. A combination of relevant mechanical engineering, electrical engineering, and programming programing skills were required to design and assemble a working prototype. The first prototype did not fulfill the given requirements, but upgrades to this initial model generated a more efficient design. Further upgrades could improve the style, speed, and efficiency of the underwater scooter. Over time, some aspects of the design, with upgrades, could have commercial applicability.

Introduction

A diver propulsion vehicle, or underwater scooter as it came to be known, is a diving accessory that offers divers many benefits as they explore the open ocean. A scooter pulls the user through the open ocean, thereby minimizing the air used and energy exerted to move around in the water. This allows for longer dives because the air in the diver's tank is conserved. Furthermore, scooters can pull a diver much faster than he or she can swim, allowing for more extensive exploration in a single dive. Underwater scooters can also make diving safer and less stressful in the case of a moderate to strong current. In addition, less exertion at deeper depths decreases the risk of decompression-related sickness. Finally, some users simply enjoy the experience of being pulled through the water [1]. The scope of this project was to develop my own underwater scooter that could reliably pull an adult through the water.

As I researched the topic, I noticed that the majority of commercially available underwater scooters had a cylindrical shape, built around a single thruster. They could be purchased in most dive shops or online with prices ranging from a few hundred dollars for a basic model to thousands of dollars for a faster and more advanced model. Some of the top manufacturers include Sea-Doo [2] and Bladefish [3].

When designing my own underwater scooter, I envisioned a flatter model, something that would turn from side to side as one glided through the water. I discovered a product called Subwing [4] which is a wing-like structure that is attached to the back of a boat. As the boat moves, Subwing allows the user to fly underwater and navigate around coral reefs. As such, I became interested in creating a wing-like structure, but instead of the boat, I wanted to make the product battery-operated with dual thrusters driving it.

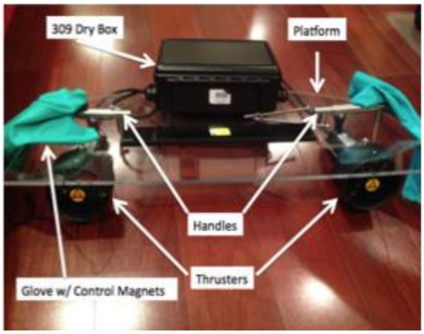

Figure 1 Overview of Final Prototype

Building the System Overview

The underwater scooter underwent two design prototypes. The first was built using an acrylic platform, a dry box that housed the electronics, and dual thrusters that drove the scooter. The scooter was powered by a 12V sealed lead acid battery. The battery powered a 556 timer, which is a dual integrated circuit chip that can be used for a range of electronic applications. In this case, the 556 timer generated a pulse-width modulation (PWM) signal to the thrusters. The motor controller was enabled and disabled by a magnet switch on the top of the dry box. Initial testing exposed several deficiencies, leading to an upgraded version of the scooter.

For the second prototype the acrylic platform was reshaped to improve its hydrodynamics. An 18.5V lithium ion battery was used instead of the 12V to drive the thrusters. A microcontroller called Arduino Uno replaced the 556 timer and generated the PWM signal to the motors. The Arduino code was programmed to operate the scooter at five speed increments from off to full power. The original magnet was used as a safety enable/disable function for the thrusters. Additionally, the five speed interval was activated by stronger magnets placed inside the thumbs of latex cleaning gloves. The user could press his or her thumb up against the side of the dry box to increase or decrease speed. Overall, the second prototype improved the scooter's functionality.

Initial Prototype

Platform Design:

The main concern when building the underwater scooter was that all the materials had to be completely waterproof to prevent leakage or rust. For the foundation of the scooter, an 18 in. x 24 in. acrylic platform was selected. The handlebars were made of nickel drawer handles that would not rust easily. These handles were mounted on both sides of the platform, approximately one-third of the length up from the bottom. These handles could be used to turn the scooter right or left, or push up or down to ascend and descend.

The underwater scooter was powered by dual SeaBotix AUV/ROV thrusters [5]. These DC motors were installed on the bottom side of the scooter towards the back end. The thrusters have three different sites at which holes were drilled and then screws were placed to attach them to the platform, as seen in Figure 2.

Figure 2 Placement of thruster and screws

Enclosure for Circuitry:

The electronics that power the scooter had to be housed in something that would guarantee absolutely no breach of water. Finding an encasing that would fit the platform and completely protect the circuitry became a difficult mechanical challenge for the design. Initially, the Plano 1412 Marine Storage Box [6] that claimed to be "water-resistant" was selected. When the box was submerged, however, water slowly seeped in due to deficiencies in the O-ring seal, making it unsuitable for the prototype. Further trial and error of the box led to a decision to test another box with a more effective o-ring seal which, ultimately, became the solution to ensuring a completely watertight encasement.

The 309 Dry Box from Underwater Kinetics [7] was chosen to use as the box to house the circuitry. The 309 Dry Box has a silicon rubber o-ring seal and when tested, it showed no indication of leakage even after it was submerged completely for 4 hours in 2 ft. of water.

This box is now used as the main component to protect the electronics of the underwater scooter. The size specifications of the Dry Box are 9.0 in. x 7.9 in. x 3.5 in. (See Figure 3). To keep the box in place, two holes were drilled through the acrylic platform on the outside of both sides of the box. There, two bolts were placed and a black block fits on top to secure the box in place. The black block can be screwed in tight when the scooter is in use or unscrewed to access the electronic circuitry as needed.

Figure 3 309 Dry Box and secured block

Electrical Circuitry:

Initially, the underwater scooter was tested using a 556 timer [8]. A 556 timer, which is a dual version of a 555 timer, is an integrated circuit that can perform a range of timer, pulse generation, and oscillator functions. In this case, the timer generated a pulse-width modulation (PWM) signal which operated the circuit. Figure 4 shows a 50% duty cycle PWM signal: one half of the time is high and the other half low. A potentiometer was soldered to a prototype board and ran the signal at approximately a 50% duty cycle.

The entire system is currently powered by a 12V lead acid battery, a standard battery commonly used to power DC motors. This battery first drives the 556 timer which emits the signal to an L298 Dual H-Bridge Motor Driver [9]. The H-Bridge was selected because the specifications show that it can handle the power required to drive the scooter. The power of the scooter can be calculated by P = ½ ρCdA V3, where P is Power, ρ is the density of the fluid, Cd is the drag coefficient, A is the frontal area, and V is the velocity. In this case, the scooter will propel a person at about .6 m/s (1.97 fps). Assume the cross section of the person is 0.5 m2, ρ is 1000 kg/m3, and Cd is 1, then the power required is equal to 50W. The electrical power required, however, is determined by the motor/thruster efficiency: Efficiency = (Mechanical power produced) / (Electrical power consumed). Efficiency is always less than 100% and for the propulsion of the scooter, we will assume it is about 50%. As a result, a production of 100W of electrical power will be required to run the scooter. The motor controller would need to produce about 8A at 12V.

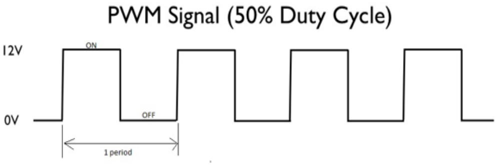

Figure 4: PWM Signal

The L298 Dual H-Bridge Motor Driver is also a dual motor driver which allows it to power two separate thrusters. It has the ability to drive the Seabotix thrusters simultaneously in either direction. In this case, it was hard wired to provide thrust in a single, counter-clockwise direction. A Littelfuse 15A, fast acting, 3AG type inline fuse [10] was installed at the plus side of the battery to prevent an excess amount of current and overheating. All the electronic components are mounted inside the Dry Box using Velcro tape. This tape keeps all the pieces secure but also allows everything to be removed quickly and effectively as needed.

Sensor and Control System:

The enable/disable function of the motor controller is directed by a Hall Effect 506 Sensor [11]. The Hall Sensor acts as a switch that can be activated by a magnet. The use of a magnetic field avoids the complications of installing a watertight switch. The Hall Effect 506 Sensor is attached to a connector on the prototype board and also tied to the logic power supply on the L298 Dual H-Bridge. The H-Bridge reads the state of the sensor to determine whether the thrusters should operate. Normally the Hall Sensor is set to 5V, but the voltage is pulled to 0V when the magnetic field from the magnet is sensed by the Hall Sensor. This enables the motor controller so the thrusters will run.

The Hall Sensor itself is epoxied at the top of the 309 Dry Box used to enclose the circuitry. Adjacent to the Hall Sensor is a small piece of scrap metal that is also epoxied to the box. This allows a magnet to be placed at the top of the sealed box and lets the scooter run continuously as a result of the magnetic attraction. The magnet itself is enclosed in waterproof tape and attached to a lanyard that can be fastened around the wrist of the user. At any time while the scooter is in use, the operator can disable the thrusters by pulling the lanyard and the magnet off the box.

Cables and Connectors:

The underwater scooter is powered by two thrusters, each with its own wire-wrap cable. These cables are fed to the battery, 556 timer, and dual motor driver to power the thrusters. As a result, two underwater connectors are positioned on the Dry Box. These connectors separate the cables outside the box which are exposed to water and the electronics inside the box, which, again, cannot get wet. In order to install the underwater connectors between the circuitry and the thrusters, two holes were drilled on each side of the box. After soldering the wires, the cables were coated with Scotchkote [12] to resist any water intake. After five minutes, the wires were connected with rubber splicing tape.

Two large holes were drilled at the top corners of the acrylic platform to feed the cabling from the motors underneath to the top of the platform. The cabling then runs across the top of the platform and attaches to the underwater connectors on the back ends of the box which houses the electronics. Several cable clamps are mounted on the platform to hold the coiled cables in place. Figure 5 shows the final assembled system.

Initial Testing:

The scooter was initially tested for functionality, speed, and buoyancy in a swimming pool with a maximum depth of 5 ft. The scooter was in use for three, fifteen minute trials. Overall observations of the scooter's performance were recorded.

The testing for the first prototype of the underwater scooter proved that it could run in the correct direction underwater. There was no leakage or other waterproofing complications. The scooter, however, ran too slowly to fulfill the requirement of efficiently pulling an adult through water. It was not possible to take an accurate measurement of the speed because of the natural inclination for the user to kick his legs to help propel forward.

Also, the magnet did not successfully remain on the box throughout the trials. As the scooter was propelled through the water, the magnet would easily slip off the top of the Dry Box from the flow of the water and, thus, the scooter would stop running. To keep it moving, the user was forced to hold the magnet on the correct spot to activate the Hall, yet this was difficult to do.

This test also proved that there was an un-

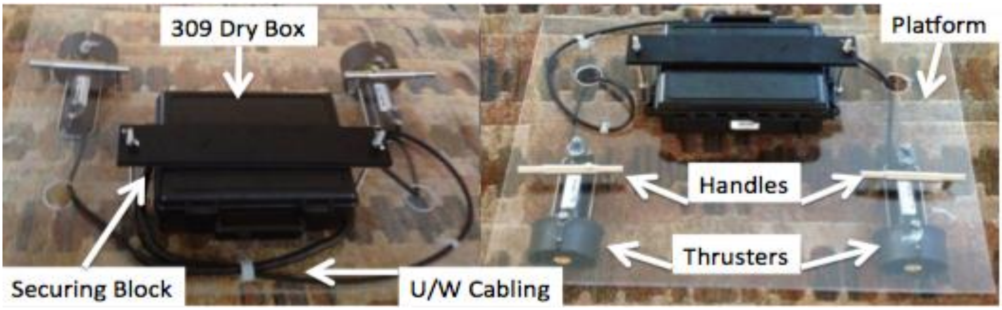

Figure 5 Final Assembled System with Underwater Cabling

even distribution of weight and this impacted the overall buoyancy of the scooter. The Dry Box and platform in the front of the scooter were positively buoyant, while the thrusters in the back produced negative buoyancy. The net buoyancy was slightly positive and, as a result, allowed the scooter to stay underwater when exerting force. This discrepancy, however, made it difficult to balance and control the scooter. The user was forced to push down on the front of the platform to evenly distribute the weight and attempt to keep the buoyancy neutral.

Upgraded Prototype

Platform Upgrade:

The acrylic platform's large surface area caused the underwater scooter to be positively buoyant toward the front. To fix this issue, the surface area needed to be reduced or cut down in size. With the help of mechanical engineering undergraduate students at FAU, a water jet was used to cut the front of the acrylic platform into a crescent shape, as shown in Figure 6. This design was also intended to make the scooter more hydrodynamic because it reduced the amount of drag produced by the excess surface area.

Electronics Upgrade:

To increase the power of the scooter, the battery was upgraded from a 12V to a 18.5V Lithium-Ion battery. The energy density of the Lithium-Ion packs is substantially greater than that of the sealed lead acid batteries. The higher voltage stayed within the specifications of the system components. Also, the Seabotix thrusters are 18V rated which explained the lack of speed while driving them at 12V. To enhance the functionality of the circuitry, the 556 timer was replaced by an Arduino Uno microcontroller [13]. Arduino is a software program written in C/C++ coding that can perform a wide range of functions. Specifically for this project, the Arduino Uno allows the scooter to run at five different speed intervals separated equally from off to full power. In addition, the programming for the Arduino code controls the direction of the thrusters and the control system of the scooter. In order to power the Arduino microcontroller, a LM317T Voltage Regulator [14] was used to step down the 18.5V to 9.9V regulated voltage to meet the input voltage specifications of the UNO. The Pololu Dual VNH5019 Motor Driver Shield for Arduino [15] was used to replace the L298 Dual H-Bridge Motor Driver as the motor controller that directs the two Seabotix thrusters simultaneously. This motor shield is compatible with the Arduino Uno and fits directly on top of it. The motor shield was chosen because it can operate under the 18.5V battery and can deliver a continuous 12-A to each Seabotix thruster.

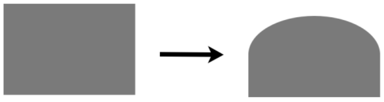

Figure 6 Progression of Platform Design from First to Second Prototype

Sensor and Control Upgrade:

In order to control the speed of the underwater scooter, two more hall sensors were added to the circuit. These hall sensors were epoxied to the inside of the Dry Box right above the cable connectors in the back. The hall sensor on the right drives the scooter faster while the hall sensor on the left reduces the speed of the scooter. When the scooter is running at full capacity, the right hall sensor will not affect the speed. When the scooter is off, the left hall sensor will not function. These hall sensors drop the current low when activated by a magnet which then causes them to perform their assigned functions. The control magnet was replaced by a neodymium magnet because it provided a stronger magnetic force than a traditional magnet. This stronger magnet more effectively remained on top of the Dry Box while the scooter was in use. Additionally, because the magnet had a ring shape, the lanyard could be reliably attached.

Two nickel plated ring magnets were used to control the speed of the scooter. These magnets are axially magnetized so only one side will activate the hall sensor. The magnets were placed in between the thumb space of two latex cleaning gloves with the correct side facing out. The other four fingers were removed from the gloves, allowing the user's fingers to have direct contact with the scooter's handles. These gloves are used as hand controls for the scooter's speed. When the user wants to change speed, he can press his thumb against the side of the Dry Box to either increase or decrease the speed, as indicated in Figure 7.

Placement on Dry Box	Function
Top	On/Off Switch
Right	Increase Speed
Left	Decrease Speed

Figure 7 Function of Each Hall Sensor

Final Testing:

To test the upgraded prototype, the scooter was similarly observed for buoyancy, speed, and overall functionality in a swimming pool with a maximum depth of 5 ft. The scooter was again tested for three, fifteen minute trials. Plus, the final trial provided data to calculate the five different speed intervals.

The testing of the second prototype proved to effectively correct the limitations of the first scooter including buoyancy, magnet placement and speed. Due to less surface area of the scooter, the scooter remained closer to neutral buoyancy. The magnet on the top of the scooter and in the thumbs of the latex gloves remained in place while the user operated the scooter. Finally, the scooter was able to deliver a higher speed and provide speed intervals as well.

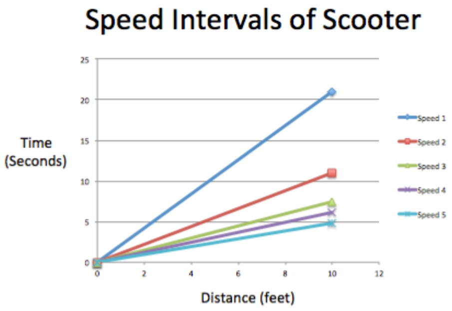

Figure 8 Graph of Calculated Five Speed Intervals

To calculate the speed of the scooter, a measuring tape measured 10 ft. along the side of the pool. The scooter ran at each speed for 10 ft. and the times were measured manually using a stopwatch. Shifts in vertical movement and slight leg movement of the user may affect the precision and accuracy of the results. Human delay must also be considered as a factor when measuring the times. From lowest speed to highest speed the times read 21.0 s (0.48 fps), 11.0 s (0.91 fps), 7.5 s (1.33 fps), 6.2 s (1.61 fps), and 4.8 s (2.08 fps). Figure 8 shows a linear relationship between the actual scooter's speed and the command signal.

Conclusion

Ultimately, the second prototype of the underwater scooter met the initial requirements of research project. From the first prototype, alteration of the platform reduced the surface area of the scooter and allowed for more neutral buoyancy. An 18.5V battery upgrade from a 12V battery significantly improved the speed of the scooter, recording a maximum speed of 2.08 fps. Additionally, the incorporation of Arduino Uno microcontroller, Pololu Dual VNH5019 Motor Driver Shield for Arduino, and LM317T Voltage Regulator considerably advanced the control mechanisms for the scooter. The addition of further magnets, including a ring shaped magnet, was also necessary to enable better control the system. Overall, the design of the underwater scooter prevented water leakage and effectively protected the circuitry. Despite fulfilling the initial requirement of this research project, further design and functionality upgrades are necessary to give the underwater scooter commercial value.

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