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THESIS

EXPERIMENTAL ASSESSMENT OF ENTANGLEMENT FOR AN UNMANNED UNDERWATER VEHICLE WITH AN OPEN, THREE-BLADED PROPELLER

by

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December 2020

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This thesis evaluates the entanglement of an unmanned underwater vehicle (UUV) propelled by an open, three-bladed propeller when operating in marine vegetation native to littoral environments. A tow tank populated with synthetic giant kelp and eelgrass was used to simulate an underwater environment. An early variant of a REMUS 100 UUV designed to conduct underwater surveillance was used for entanglement tests. Three different entanglement tests were conducted. A vegetation density and constant entanglement test, conducted by changing vehicle steady-state speed and marine vegetation density, showed an increased entanglement risk for eelgrass and astern propulsion operations, and increased vegetation density. A lateral placement entanglement test, conducted by changing the marine vegetation location relative to the vehicle center line, showed an increase in entanglement risk for vegetation located close to the propeller and indicated a relationship between propeller diameter, vegetation location, and entanglement. A preliminary accelerating speed entanglement test, conducted by changing the vehicle speed at the propeller entry to a vegetation field, showed that as the ratio of vehicle speed at propeller entrance to steady-state speed decreased, the likelihood of an entanglement increased. Recommended future work includes entanglement testing for different UUV types, testing in the operating environment, and assessing devices or procedures intended to reduce entanglement risk.

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EXPERIMENTAL ASSESSMENT OF ENTANGLEMENT FOR AN UNMANNED UNDERWATER VEHICLE WITH AN OPEN, THREE-BLADED PROPELLER

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This thesis evaluates the entanglement of an unmanned underwater vehicle (UUV) propelled by an open, three-bladed propeller when operating in marine vegetation native to littoral environments. A tow tank populated with synthetic giant kelp and eelgrass was used to simulate an underwater environment. An early variant of a REMUS 100 UUV designed to conduct underwater surveillance was used for entanglement tests. Three different entanglement tests were conducted. A vegetation density and constant entanglement test, conducted by changing vehicle steady-state speed and marine vegetation density, showed an increased entanglement risk for eelgrass and astern propulsion operations, and increased vegetation density. A lateral placement entanglement test, conducted by changing the marine vegetation location relative to the vehicle center line, showed an increase in entanglement risk for vegetation located close to the propeller and indicated a relationship between propeller diameter, vegetation location, and entanglement. A preliminary accelerating speed entanglement test, conducted by changing the vehicle speed at the propeller entry to a vegetation field, showed that as the ratio of vehicle speed at propeller entrance to steady-state speed decreased, the likelihood of an entanglement increased. Recommended future work includes entanglement testing for different UUV types, testing in the operating environment, and assessing devices or procedures intended to reduce entanglement risk.

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List of Acronyms and Abbreviations

AUVs	autonomous underwater vehicles
DOD	Department of Defense
DFG	derelict fishing gear
EOD	explosive ordnance disposal
MCM	mine countermeasures
NPS	Naval Postgraduate School
ROV	remotely operated vehicle
REMUS	Remote Environmental Measuring UnitS
ROKN	Republic of Korea Navy
RPM	revolutions per minute
UUV	unmanned underwater vehicle
USN	U.S. Navy
USW	undersea warfare
VSW	very shallow water

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Executive Summary

This thesis evaluates the entanglement of an unmanned underwater vehicle (UUV) operating in marine vegetation common to littoral environments. Entanglement was assessed for a traditional UUV with an open, three-bladed propeller transiting a vegetation field at a constant heading and depth. Factors such as the vegetation density, vegetation placement and configuration, propeller revolutions per minute (RPM), and vehicle speed were varied to determine their impact on vehicle entanglement. Results provide insight to the mechanism of entanglement and operating conditions that result in a high or low likelihood of entanglement. These results are of particular interest to the Department of Defense as the military's use of UUVs in littoral environments becomes more prevalent.

Experimental tests were conducted in a tow tank located at the Naval Postgraduate School. Synthetic eelgrass and synthetic giant kelp plants anchored to a plate located at the bottom of the tow tank were used to simulate marine vegetation common to the littorals. The UUV tested in this work was an early variant of the Remote Environmental Measurement UnitS (REMUS) 100 manufactured by Hydroid. The REMUS 100 was attached to a movable carriage located on top of the tow tank using a vertical sting and custom-made adapter. This configuration allowed the REMUS 100 to self-propel itself, and the attached movable carriage, down the tank at a constant depth and heading. Vehicle speed and direction of travel (forward versus astern) was adjusted by changing the propeller RPM of the REMUS 100. A position sensor was used to correlate propeller RPM to the vehicle's steady state speed and to determine the vehicle's speed as a function of position (accelerating speed).

Three different entanglement tests were conducted: a vegetation density and constant speed test, a lateral placement test, and an accelerating speed test. In the vegetation density and constant speed test, the density of giant kelp and eelgrass was varied, and the vehicle steady state speed and propulsion direction (forward versus astern) was varied by changing the propeller RPM. In the lateral placement test, the eelgrass and giant kelp position was offset different distances from the center line of the vehicle. In the accelerating speed test, the propeller entrance speed to an eelgrass field was varied by providing the vehicle a limited distance to accelerate up to speed and thus resulted in the vehicle not being at its steady state speed when it passed through the vegetation field. The different entanglement conditions

identified for each test run were no entanglement, an entanglement event, and an entanglement kill; these conditions were assessed by visually observing the speed of the vehicle as it entered, transited, and exited the vegetation field. During a no entanglement condition, vehicle speed remained constant throughout the entirety of the run. An entanglement event condition was characterized by a decrease in vehicle speed caused by vegetation wrapping around the hub of the vehicle's propeller, but not actually stopping the vehicle, so that eventually the vehicle was able to pass through the vegetation field. An entanglement kill condition was characterized by a decrease in the vehicle speed to zero caused by extensive vegetation wrapping of the vehicle's propeller.

A 2 (marine vegetation type) x 4 (marine density configurations) x 3 (vehicle speeds) x 2 (propulsion directions) x 3 (trials) design was used for the vegetation density and constant speed test. The two marine vegetation types used were giant kelp and eelgrass. The four different marine vegetation density configurations considered were high, medium, low, and single. Three vehicle steady state speeds corresponding to three different propeller RPMs (600, 900, and 1200) were tested. Test runs were conducted for the REMUS 100 operating forward propulsion (clockwise propeller rotation) and astern propulsion (counterclockwise propeller rotation). Three trials were conducted for each design point. Results from this initial vegetation density and constant speed test were used to determine the speed at which entanglement began to occur for each density configuration (entanglement threshold). The highest speed, corresponding to the highest RPM at which entanglement occurred for each density configuration was used as an initial testing point to find this threshold. Testing results were analyzed with respect to the entanglement risk, classified as very high, high, moderate, low, and minimal, associated with each test condition. Major findings were that eelgrass entanglement risk is higher than giant kelp entanglement risk, entanglement risk is higher when operating astern, and there is a critical vegetation density level, above which entanglement is very likely.

A 6 (placement configuration) x 2 (propulsion directions) x 3 (trials) design was used for eelgrass lateral placement testing and a 4 (placement configuration) x 2 (propulsion directions) x 3 (trials) was used for giant kelp lateral placement testing. For the eelgrass lateral placement testing, six placement configurations were used to offset a single eelgrass plant from the propeller center line; three configurations positioned the plant at different distances to the left of the propeller center line and three configurations positioned the

plant at different distances to the right of the propeller center line. For the giant kelp lateral placement testing, four placement configurations were used to offset a single giant kelp plant from the propeller center line; two configurations positioned the plant at different distances to the left of the propeller center line and two configurations positioned the plant at different distances to the right of the propeller center line. Tests were conducted for forward and astern propulsion and three trials were conducted for each design point. Testing results were analyzed by plotting the number of entanglements that occurred for each vegetation placement configuration. Major findings were that the number of entanglements increases as the distance between the marine vegetation and propeller decreases and that the vehicle's propeller diameter impacts entanglement.

The accelerating speed test served as a preliminary analysis of the impact that the number of propeller revolutions during the propeller transit through the vegetation field has on vehicle entanglement. This evaluation was done by varying the vehicle speed for a range of RPMs. Factors changed for each test point were propeller RPM and the distance between the propeller and front of the vegetation field. Testing results were analyzed by plotting the likelihood of entanglement as a function of the vehicle's speed ratio. The vehicle's speed ratio represents the ratio between the vehicle's speed at the propeller entrance to the vegetation field and the vehicle's steady state speed. Major findings were that the likelihood of entanglement increases as the speed ratio decreases and that the line between entanglement and no entanglement is dynamic and unstable.

Additional data is required to assess the relationship between the number of propeller revolutions in a vegetation field and entanglement that was explored preliminarily in the accelerating speed test. It is also recommended that entanglement testing be conducted in an open ocean environment to identify other entanglement concerns such as silt and other marine vegetation types. Real-world tests would also allow the full propulsion capability of the REMUS 100 to be tested. Future work on entanglement solutions for UUVs is also required, especially as they become more operationally relevant. Possible solutions include entanglement protection devices and operational procedures. Finally, entanglement testing for other UUV types that use different propulsive mechanisms, such as the GhostSwimmer that is propelled by flapping fins, should be conducted.

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CHAPTER 1:
Introduction

1.1 Chapter Introduction

This thesis evaluates the entanglement of an unmanned underwater vehicle (UUV) operating in marine vegetation native to littoral environments. When operating in littoral waters, UUVs are at risk of becoming entangled in shallow water marine vegetation, such as giant kelp and eelgrass. While many UUV types with different propulsive mechanisms are in use today, this work assesses entanglement of a traditional UUV with an open, three-bladed propeller.

1.2 Background and Motivation

Currently, the Department of Defense (DOD) uses UUVs or autonomous underwater vehicles (AUVs) for sea sensing and mine countermeasures (MCM) missions [1]. By 2025, the DOD plans to use them to support Undersea Warfare (USW) missions in areas where submarines currently operate and in shallower areas where manned platforms cannot operate [1]. A major barrier to UUV operations are fishing nets and kelp beds in these littoral environments that can entangle, damage, and result in the loss of UUVs [2]. UUV entanglement is a significant concern to the Navy and its various entities, such as the explosive ordnance disposal (EOD) community. Possible solutions to entanglement being explored include incorporating mechanical cutters, line deflectors, and changes to vehicle design [3].

1.3 Marine Vegetation in Littoral Environments

Systems that are able to entangle divers are an entanglement threat for UUVs [4]. Marine vegetation present in the littoral operating environments, such as giant kelp and eelgrass, is an entanglement threat for UUVs.

An example of marine vegetation commonly found in the littorals is kelp forests or kelp beds composed of dense groupings of brown algae or kelp [5]. These kelp forests are found worldwide, including the western portions of North and South America, the southern edge of Africa and Australia, and islands near Antarctica [6]. Figure 1.1 shows the global

distribution of kelp forests; the most common species of kelp that forms these kelp forests is the Macrocytic type, more commonly known as giant kelp.

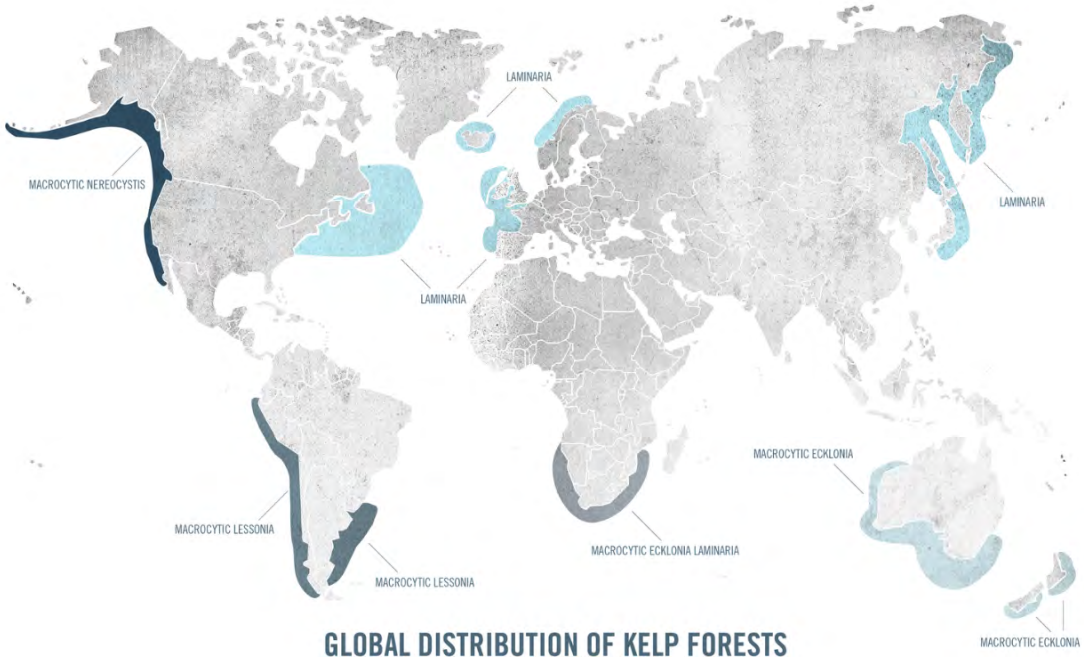

Figure 1.1. Global Distribution of Kelp Forests. Source: [7].

Giant kelp, shown in Figure 1.2, is the largest species of kelp. It is native to shallow waters (5 to 30 meters) with a rocky seafloor which are commonly found in North and South America, South Africa, Southern Australia, and New Zealand [8], [9]. Giant kelp is comprised of round stipes that have several blades that are attached via gas-filled floats [10]. Giant kelp undulates in the ocean currents due to the tough and flexible stipes of the plant [11]. The blades and stipe of giant kelp are supported by a holdfast that attaches to the seafloor [9]. Giant kelp growing in the ocean is referred to as a kelp forest and can form closed canopies over a reef, even in areas with a low density giant kelp population (one plant per 10-15 m^2) [12]. Giant kelp is an entanglement concern for marine vessels, divers and swimmers transiting in the ocean [13].

Figure 1.2. Giant Kelp Forest Commonly Found in Cold, Littoral Waters. Source: [14].

Another type of marine vegetation found in littoral environments is eelgrass. Eelgrass, shown in Figure 1.3, grows in large beds in bays, inlets, and estuaries in the North Atlantic [15]. Eelgrass is found on the East Coast of the United States in water depths less than three meters and on the west coast of the United States in water depths greater than five meters [16]. Eelgrass is comprised of a thick stem about 2 to 5 centimeters long (rhizome) that has several roots spaced 1 to 3.5 centimeters apart and long, thin leaves that can grow up to 1.2 meters long and 2 to 12 millimeters wide [16].

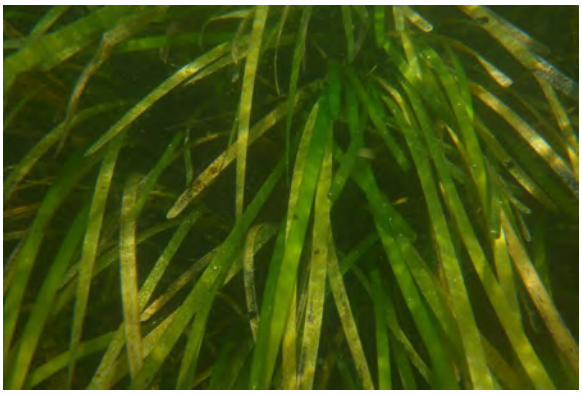

Figure 1.3. Eelgrass Bed Commonly Found in Shallow Waters. Source: [15].

1.4 UUV Types and Entanglement

While previous research has evaluated the impact that propulsive mechanism type has on UUV efficiency and endurance, there is no publicly available research that has evaluated the impact that propulsive mechanism type has on the likelihood of entanglement in an operational environment. A majority of UUVs employed use rotary screw propellers, rotating control surfaces, and have a cylindrical hull form [17]. While experimental evidence is limited, operators have found that these rotating components are susceptible to entanglement, especially in littoral environments where marine vegetation is abundant [18]. Although UUVs propelled by rotary screw propellers are the most common, some UUVs use propulsive and control mechanisms that simulate marine life, while others use tunnel thrusters for propulsion and maneuverability [17].

Figure 1.4 shows the Remote Environmental Measuring UnitS (REMUS) 100, a traditional UUV manufactured by Hydroid. The REMUS 100 is a man-portable UUV propelled by an open three-bladed propeller attached to a DC motor [19]. Dimensions of the REMUS 100 are variable due to its customized payload; however, a baseline variant has a diameter of 19 centimeters, length of 170 centimeters, weight of 36 kilograms, maximum operating depth of 100 meters, and a velocity range of 0 to 2.572 m/s (0 to 5 knots) [19].

Figure 1.4. REMUS 100 UUV that Uses an Open Three-Bladed Propeller for Propulsion. Source: [20].

The REMUS 100 was initially designed to monitor coastlines and perform ocean surveillance and mapping missions in an area by operating in a lawnmower-like pattern [20]. Other applications of the vehicle include MCM, undersea search and survey, and homeland

security [20]. The U.S. Navy (USN) first employed the REMUS 100 in Operation Iraqi Freedom to conduct port clearance operations; today, it is the USN's primary mine-hunting platform [21].

Figure 1.5 shows the GhostSwimmer, a biomimetic AUV developed by Boston Engineering. The GhostSwimmer propels itself through the water using a moving tail and flapping pectoral fins [22]. The GhostSwimmer has a length of 1.52 meters, width of 0.36 meters, height of 0.46 meters, weight of 40.8 kilograms, and a maximum operating depth of 100 meters [22]. The GhostSwimmer is designed to support intelligence, surveillance, and reconnaissance (ISR), very shallow water (VSW) MCM, and explosive ordnance disposal (EOD) missions [23].

Figure 1.5. GhostSwimmer AUV that Uses Flapping Fins for Propulsion. Source: [22].

Figure 1.6 shows the BlueROV2, a box-shaped remotely operated vehicle (ROV), designed by Blue Robotics. The BlueROV2 uses six T200 thrusters that provide propulsion and vectored thrust control [24]. The BlueROV2 has a length of 45.7 centimeters, width of 33.8 centimeters, height of 25.4 centimeters, weight of 10 to 11 kilograms, maximum operating depth of 100 meters, and a maximum speed of 3 knots [24].

Figure 1.6. Blue Robotics BlueROV2 that Uses Tunnel Thrusters for Propulsion. Source: [24].

While entanglement is a concern for all UUV types, this thesis quantifies and evaluates the entanglement of a traditional design propelled by an open three-bladed propeller when operating in a simulated littoral environment.

1.5 Previous Work

Currently, UUV entanglement in marine vegetation is mostly anecdotal; however, the risk of propeller entanglement in other types of marine objects, such as nets, is an identified issue. One study evaluated navigational threats to Korean naval ships caused by derelict fishing gear (DFG), such as nets and lines [25]. The study reviewed six years (2010-2015) of case studies related to the entanglement of the Republic of Korea Navy (ROKN) vessels in DFG [25]. During this review, it was found that the propellers or shafts of vessels were entangled in DFG in 2386 cases; this is of particular concern because propeller entanglement compromises the stability and maneuverability of the vessel [25].

Propeller entanglement issues are further demonstrated by various patents for devices designed to disentangle and entangle marine vessels. Figure 1.7 shows the UUV fishing net winding prevention device designed to be mounted on the bow of an UUV [26]. The device has two rotating blades, powered by a rotating drive device, that are able to cut a fishing net in an entanglement case [26].

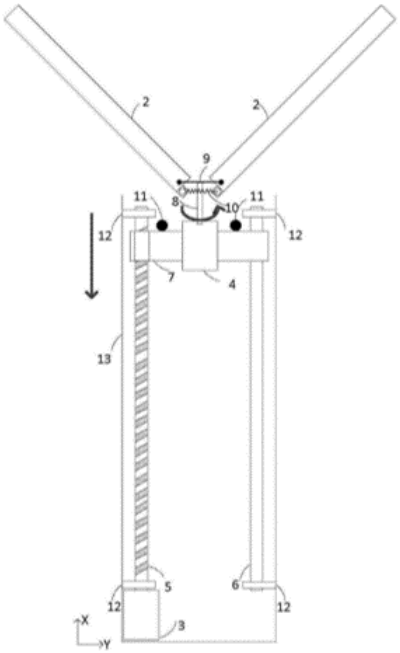

Figure 1.7. Fishing Net Winding Prevention Device Designed to Disentangle UUVs Caught in Fishing Nets. Source: [26].

Figure 1.8 shows an external (shown by Figure 2A) and internal (shown by Figure 2B) view of the concentric cutting assembly device designed for underwater vehicles operating in fishing areas [27]. When mounted on an UUV, the device is able to cut through nets and other objects using an inner cutter with rotating teeth and an outer, concentric cutter with fixed teeth [27]. If entanglement occurs, the device can cut through an object or net using these inner and outer cutting components [27].

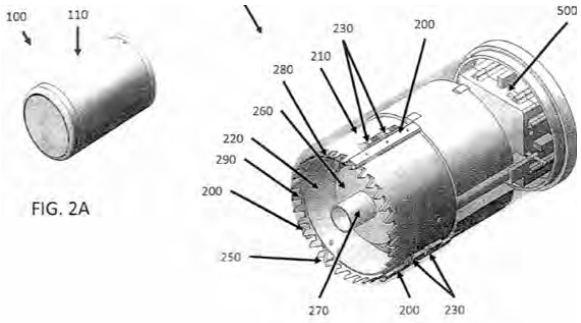

Figure 1.8. Concentric Cutting Assembly Designed to Cut Fishing Nets and Other Objects Entangled on Underwater Vehicles. Source: [27].

Figure 1.9 shows the watercraft arresting system composed of an entanglement subsystem and a deployment subsystem [28]. The deployment subsystem drops the entanglement subsystem, which is a net with multiple net arms, in the path of a waterborne vessel [28]. The system slows or stops the vessel due to the propeller being entangled in the net arms of the entanglement subsystem [28].

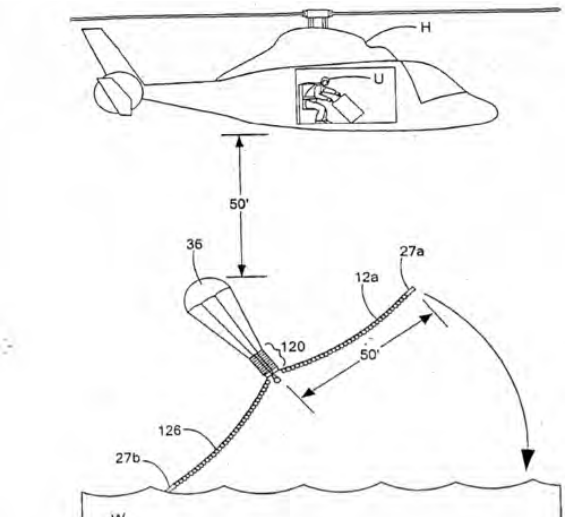

Figure 1.9. Watercraft Arresting System Designed to Entangle and Arrest Waterborne Vessels. Source: [28].

1.6 Objectives

The objective of this thesis was to evaluate the entanglement of an UUV operating in marine vegetation common to a littoral environment. While UUV entanglement is a known problem, prior research analyzing entanglement and conditions required for entanglement is not publicly available. This work considered the impact that UUV speed and propeller revolutions per minute (RPM), marine vegetation density and configuration, and marine vegetation type had on entanglement for an UUV using an open, three-bladed propeller for propulsion.

1.7 Outline

Entanglement of UUVs is a concern for the DOD, especially as the use of UUVs in the littorals becomes more prevalent. This work assesses the entanglement of a REMUS 100 UUV when maneuvering through marine vegetation common to littoral waters. Chapter 2 discusses equipment and facilities used for testing, Chapter 3 discusses the vehicle calibration and marine vegetation characterization conducted prior to testing, Chapter 4 discusses the testing procedure and design of experiments, Chapter 5 provides the entanglement testing results and analysis, and Chapter 6 discusses recommendations for future work.

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CHAPTER 2:
Equipment and Facilities

2.1 Chapter Introduction

This chapter discusses the equipment and facilities used to conduct entanglement testing of an UUV propelled by an open, three-bladed propeller. A tow tank was used to conduct test runs of a REMUS 100 UUV operating at different speeds and marine vegetation configurations. Synthetic giant kelp and eelgrass plants used to simulate marine vegetation common to littoral waters were anchored to a marine vegetation configuration plate that was used to vary vegetation concentration and placement during entanglement testing.

2.2 Tow Tank

Figure 2.1 shows the tow tank used in this thesis. The tow tank, located in Halligan Hall at the Naval Postgraduate School (NPS), is 10.9728 meters (36 feet) long, has a width of 0.9144 meters (3 feet), and is 1.2192 meters (4 feet) tall. The tow tank was filled with fresh water to a depth of 0.9144 meters (3 feet) to support UUV entanglement testing. An aluminum U-channel and a Plexiglas plate were mounted on top of a moving carriage located on top of the tow tank. This moving carriage is a 1.905 centimeters (3/4 inch) thick aluminum plate that is able to move the entire length of the tank on top of two parallel bars. The moving carriage plate rides on top of ball bearings which minimize friction but do not eliminate it. Typically, the moving carriage is attached to a cable pulley mechanism; however, this was removed to allow the moving carriage to be propelled freely by the vehicle. The U-channel mounted on top of the moving carriage provided an attachment point for a vertical sting used to maintain vehicle depth and heading. The Plexiglas plate was used to reflect ultrasonic pulses produced by a Senix ToughSonic 30 ultrasonic position sensor mounted on the aft end of the tow tank. The ultrasonic sensor and Plexiglas vertical plate were used to determine the position of the vehicle and moving carriage assembly in the tow tank as a function of time. This position versus time data was used to determine the forward speed of the system. Rigging equipment was installed on I-beams above the tow tank to lift the REMUS in and out of the tow tank.

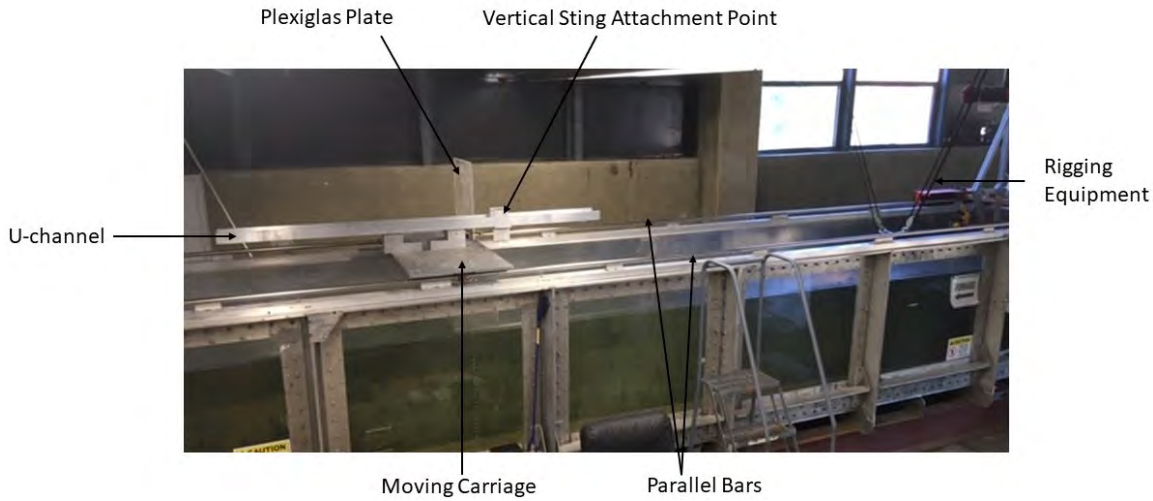

Figure 2.1. NPS Tow Tank Used to Conduct REMUS Entanglement Testing.

2.3 REMUS 100 UUV

Figure 2.2 shows the REMUS 100 variant used in this work. The vehicle (Part Number: 153734, Serial Number: SN01250), provided by the Center for Autonomous Vehicle Research at NPS, was an early model of the REMUS 100 manufactured in 2002. The REMUS variant used has a bow diameter of 18.4 ± 0.2 centimeters (7.25 ± 0.06 inches), length of 154.94 ± 0.2 centimeters (61 ± 0.06 inches), and weight of 36.3 ± 0.45 kilograms (80 ± 1 pounds).

Figure 2.2. REMUS 100 Variant Used for Entanglement Testing.

Figure 2.3 shows an aft and side view of the open, three-bladed propeller. The propeller hub has a diameter of 2.22 ± 0.03 centimeters (7/8 ± 1/128 inches) and a blade diameter of 11.43 ± 0.03 centimeters (4.5 ± 1/128 inches). Each propeller blade is 6.03 ± 0.2 centimeters (2 and 3/8 ± 0.06 inches) long. The propeller operating range is 0 to 2000 RPM in the ahead direction (clockwise rotation with respect to the front of the vehicle) and astern direction (counterclockwise rotation with respect to the front of the vehicle). Diameters of particular interest for entanglement were the REMUS 100 propeller hub diameter and the REMUS blade tip diameter.

Figure 2.3. Aft and Side View of the REMUS 100 Open Three-Bladed Propeller.

2.4 Synthetic Marine Vegetation

Synthetic marine vegetation was used to simulate real-world vegetation to eliminate additional work required to keep living vegetation samples alive throughout the testing process. Synthetic vegetation, typically used in aquariums, manufactured by Bio Models Company was used to simulate a littoral environment.

2.4.1 Synthetic Giant Kelp

Figure 2.4 shows one of the three-foot, single strand, synthetic giant kelp plants manufactured by Bio Models Company used to simulate giant kelp. Each synthetic giant kelp plant was attached to a 3/8"-16 nylon threaded anchor 2" long. Each giant kelp plant was mounted to a Plexiglas plate placed in the tow tank using the nylon anchor. The synthetic giant kelp was made out of a plastic material (Plastikelp) that is buoyant, flexible, and durable [29].

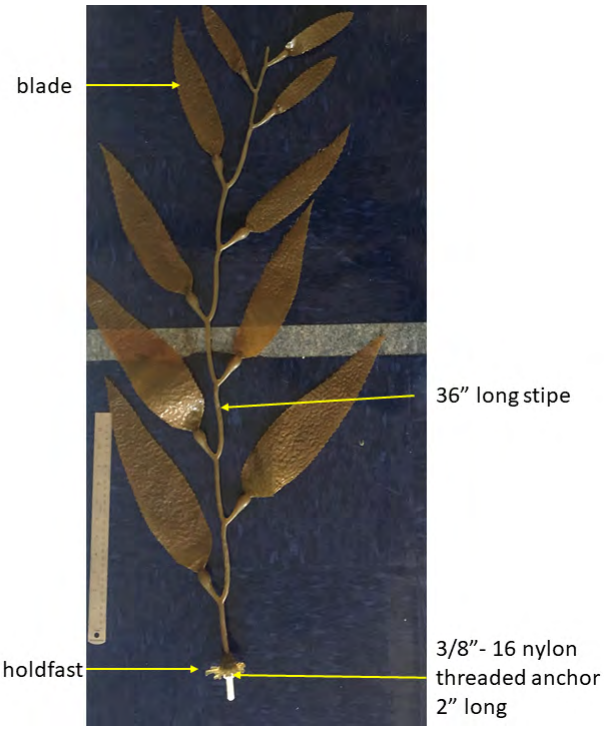

Figure 2.4. Bio Models Company Synthetic Giant Kelp Used to Simulate Giant Kelp.

2.4.2 Synthetic Eelgrass

Synthetic eelgrass, shown in Figure 2.5, was used to simulate eelgrass. Like the synthetic giant kelp, the synthetic eelgrass was manufactured by Bio Models Company. Each synthetic eelgrass plant was composed of 20 x 36-inch blades and a 1/4"-20 nylon screw 2" in length attached to the bottom of it for anchoring purposes.

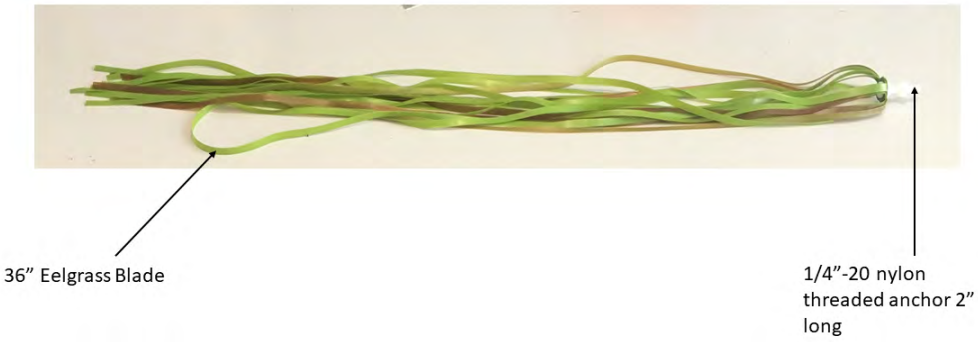

Figure 2.5. Synthetic Eelgrass Plant Used to Simulate Eelgrass.

2.5 Marine Vegetation Configuration Plate

A 0.9144 meter (3 feet) wide and 0.6096 meter (2 feet) long Plexiglas marine vegetation configuration plate, shown in Figure 2.6, was used to secure the synthetic giant kelp and eelgrass to the bottom of the tank. Additionally, it allowed for the vegetation configuration to be changed quickly. The plate was modified by drilling 35 (5 across and 7 down) 3/8" clearance holes used to rigidly attach each giant kelp plant at its anchor point and with 30 (6 across and 5 down) 1/4" clearance holes used to attach each eelgrass plant at its anchor point. Larger clearance holes were extruded on each corner of the plate to facilitate lifting the plate in and out of the tank using ropes.

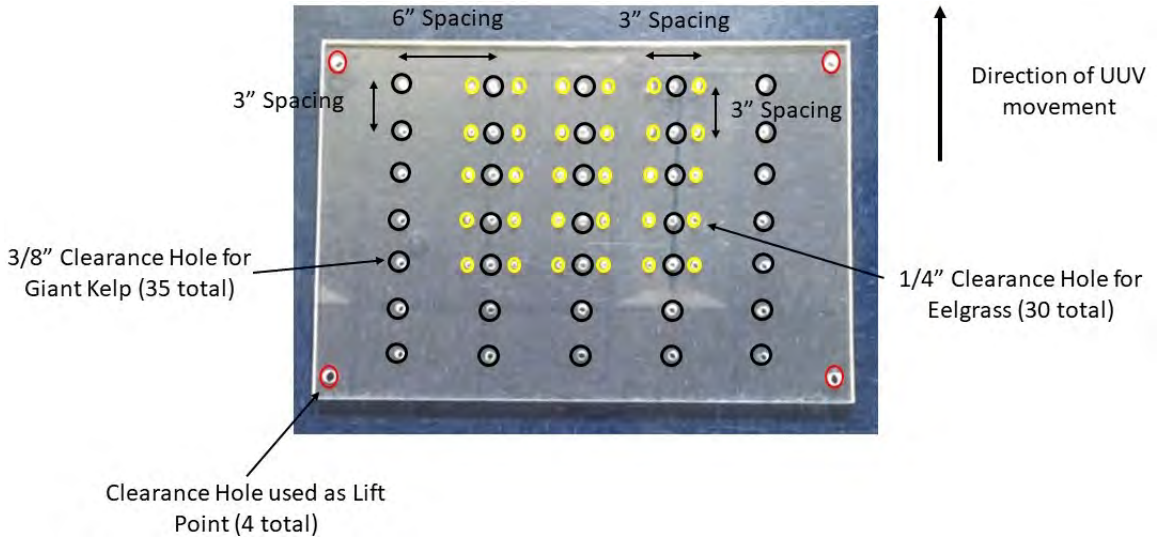

Figure 2.6. Marine Vegetation Configuration Plate Used to Vary Giant Kelp and Eelgrass Concentration and Placement for Entanglement Testing.

2.6 Test Fixture

Figure 2.7 shows the test fixture used for entanglement testing. The REMUS was operated in a tethered (non-autonomous) configuration at a constant RPM, heading, and depth. The REMUS was attached to the moving carriage assembly via a vertical sting and 3D printed adapter designed to maintain heading and depth. The vertical sting has 42 machined holes that are able to attach to the moving carriage assembly. The sting was attached to the moving carriage assembly via the fourteenth hole, resulting in a vehicle depth range (from the top of the vehicle's hull) of 10.91 to 16.97 centimeters (4.29 to 6.66 inches) below the surface of the water. The range of vehicle depth is due to water evaporation that occurred over the course of the testing processing. The sting has two machined holes on the bottom of it which were used as the attachment point for the adapter and the vehicle. While the REMUS heading and depth was constrained, the vehicle was free to pitch during test runs. The adapter was designed to fit over the handle attached to the REMUS 100 (see Appendix for adapter engineering drawing). The REMUS was connected to the Hydroid Power/Network Interface via a cable plugged into its connection port. This Hydroid Power/Network Interface was connected to the Linksys Wireless-G Broadband Router Model WRT54G with an Ethernet cable. The Getac laptop was connected to the REMUS network established with the Linksys

Router. REMUS VIP software installed on the Getac laptop was used to monitor REMUS parameters during operation and to change the propeller RPM.

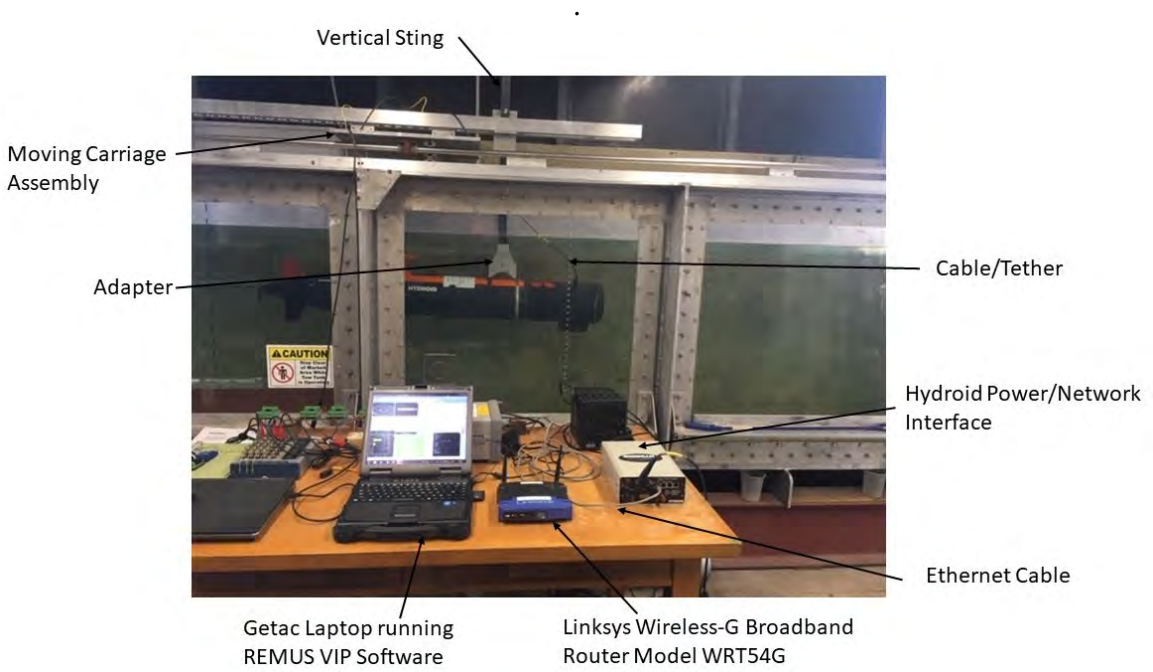

Figure 2.7. Experimental Setup for REMUS Speed Calibration and Entanglement Runs.

2.7 Chapter Summary

This chapter provided the equipment and facilities used to conduct entanglement testing of an early REMUS 100 UUV variant. Synthetic giant kelp and eelgrass plants manufactured by Bio Models Company were used to simulate real-world marine vegetation. These plants were attached to a marine vegetation configuration plate in different configurations and placed in the tow tank for entanglement testing. The REMUS was fixed to a moving carriage assembly via a vertical sting and adapter to maintain a constant heading and depth during testing. Propeller RPM was controlled using REMUS VIP software. The next chapter discusses the vehicle speed calibration and marine vegetation characterization conducted prior to entanglement testing.

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CHAPTER 3:
Calibration and Characterization

3.1 Chapter Introduction

This chapter discusses the vehicle speed calibration and marine vegetation characterization conducted prior to entanglement testing. A speed calibration was conducted to determine the relationship between propeller RPM and vehicle speed when attached to the test fixture. Dimensional and material properties of the synthetic giant kelp and eelgrass used were measured. Additionally, properties associated with the synthetic giant kelp sample were compared to a single representative piece of real giant kelp sample to identify similarities and differences between the simulated littoral environment and real-world environment.

3.2 Vehicle Speed Calibration

A speed calibration was conducted for the REMUS 100 when attached to the moving carriage assembly. Voltage and time data generated during calibration runs was used to evaluate vehicle speed as a function of time and speed as a function of position for the range of RPMs tested.

3.2.1 Vehicle Speed Calibration Setup

Figure 3.1 shows the tow tank setup used to conduct a speed calibration for the REMUS. The speed calibration provided the relationship between vehicle RPM and speed when attached to the moving carriage assembly. As the moving carriage assembly moved along the length of the tow tank, a Senix ToughSonic 30 Ultrasonic Position Sensor Model TSPC-15S sensor powered by a Keysight E3631A 80W Triple Output DC Power Supply (6V, 5A±25V, 1A) generated ultrasonic signals that reflected off of the Plexiglas plate. The ultrasonic sensor outputted a voltage proportional to the distance that the Plexiglas plate was from the sensor; this output voltage was channeled through a National Instruments NI-USB-6363 X-Series Multifunction DAQ connected to a Dell Precision 7710 Laptop via a USB cable. A MATLAB script running on the laptop was used to collect 15 seconds of voltage and

time data for the carriage assembly movement. Voltage, corresponding to position, and time data was used to plot speed as a function of time and speed as a function of position.

Figure 3.1. REMUS 100 Speed Calibration Experimental Setup.

3.2.2 Vehicle Speed Calibration Procedure

The REMUS VIP software was used to set the propeller RPM as shown in Figure 3.2. RPM could be changed in increments of 10 by selecting the up and down arrows in the REMUS VIP software.

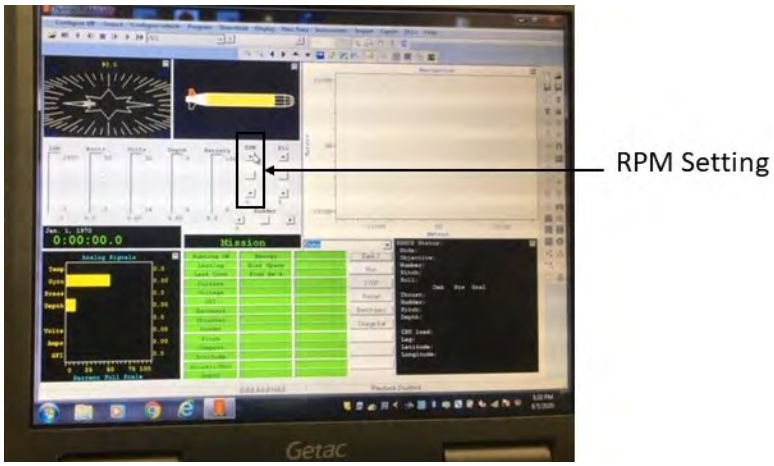


Figure 3.2. Setting REMUS RPM using the REMUS VIP Software.

RPM was slowly increased to determine the propeller RPM corresponding to the vehicle speed required to overcome the frictional force imposed by the moving carriage assembly. 560 RPM was required to generate enough force to propel the vehicle forward when attached to the test fixture.

A speed calibration was conducted for RPMs ranging from 600 to 1700 in 100 RPM increments. Speed calibration runs for 1700 to 2000 RPM were not conducted based on the length of the tank and stopping distance required for the REMUS 100. The vehicle was launched from the front of the wave absorbing beach located at the end of the tow tank as shown in Figure 3.3. The vehicle and moving carriage assembly were held stationary until the required RPM was set using the REMUS VIP software. The MATLAB code was started in order to collect voltage and time data as the REMUS traversed the length tank. At the end of the run, the RPM was reset to 0 and the REMUS and moving carriage assembly were manually moved back to the starting point.

Figure 3.3. Test Run Start Point.

3.2.3 Speed Calibration Data Analysis Method

Time and voltage data of the vehicle when attached to the moving carriage assembly was collected for the propeller RPM range of 600 to 1700. A MATLAB script was used to determine vehicle speed as a function of time and position for each propeller RPM tested. First, the voltage data was converted to a position using the sensor gain of 76.2 centimeters (30 inches) per volt. Next, a linear regression and curve fit were used to approximate the steady state speed as a function of time. Then, the equation of motion shown in Equations 3.1 and 3.2 was applied to determine vehicle speed as a function of time and position.

$$\Sigma F = T - D = ma \tag{3.1}$$

where F is force, T is thrust, D is drag, m is mass, and a is acceleration.

Assuming that the propeller thrust is not a function of speed and the drag coefficient is not a function of speed, Equation 3.1 can be rewritten as:

$$\frac{dv}{dt} = \frac{T}{m} - \frac{\frac{1}{2}\rho S_a C_d}{m} v^2 \tag{3.2}$$

where $\frac{dv}{dt}$ is the change in vehicle velocity with respect to time, ρ is the density of the medium (water), S_a is the surface area of the vehicle, C_d is the coefficient of drag, and v is vehicle speed.

Vehicle speed as a function of time, provided in Equation 3.3, is determined by integrating Equation 3.2, which is a separable differential equation, and using the initial condition that the speed at time zero seconds is zero m/s ($v(0) = 0$). Unknown, constant values are represented by the coefficients A and B shown by Equations 3.4 and 3.5.

$$v(t) = \sqrt{\frac{A}{B}} \tanh\left(\sqrt{AB}\, t\right) \tag{3.3}$$

$$A = \frac{T}{m} \tag{3.4}$$

$$B = \frac{\frac{1}{2}\rho S_a C_d}{m} \tag{3.5}$$

Vehicle speed as a function of position can be determined using Equations 3.6 and 3.7. First, Equation 3.3 is integrated to solve for position.

$$s(t) = \frac{1}{B} \ln\left(\cosh\left(\sqrt{AB}\, t\right)\right) \tag{3.6}$$

Then, Equation 3.6 is rearranged to solve for time as a function of position, as shown by Equation 3.7

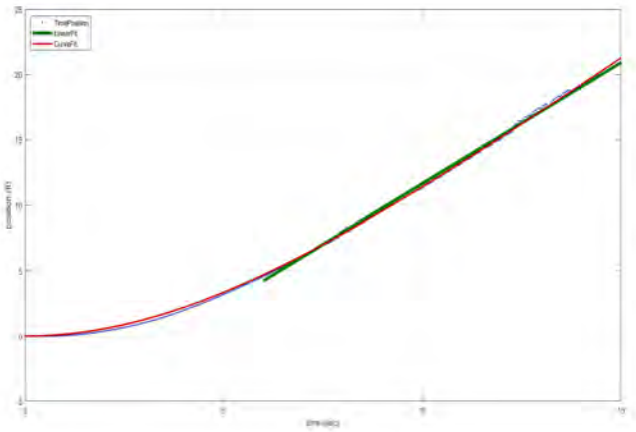
$$t(s) = \frac{1}{\sqrt{AB}} \operatorname{arcosh}\left(e^{Bs}\right) \tag{3.7}$$

Finally, the time as a function of position determined using Equation 3.7 can be substituted into Equation 3.3 to find vehicle speed as a function of position.

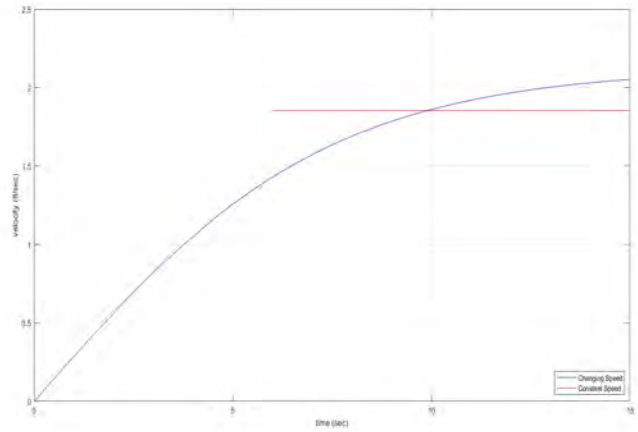
These equations and results were used to plot vehicle position versus time, vehicle speed versus time, and vehicle speed versus vehicle position. Steady state speed corresponding to each propeller RPM was determined by averaging three vehicle speed points corresponding to the last two seconds of each run. Steady state speed error was determined by calculating the 95% confidence interval for each RPM. Vehicle speed as a function of position was used to analyze forward speed entanglement test results and will be discussed in a later chapter.

3.2.4 Speed Calibration Data Analysis Example: 900 RPM

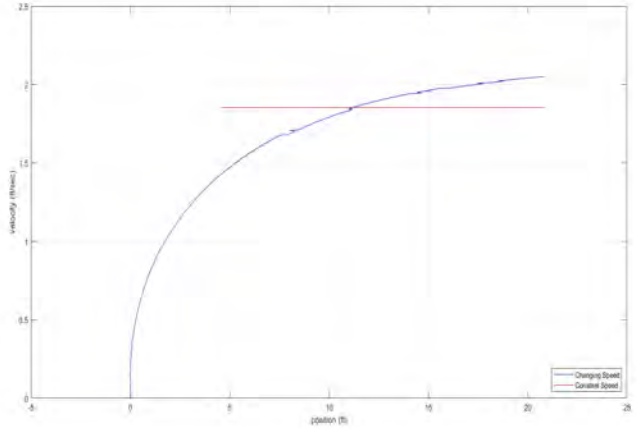
This section provides a speed calibration data analysis example for 900 RPM. Voltage and time data for the 900 RPM run was exported as a .csv file. The MATLAB script called this file to solve and plot position versus time, speed versus time, and speed versus position. Figure 3.4 shows each of these plots. Figure (a) shows entire data set (15 seconds) for vehicle position versus time, a linear regression for vehicle steady state speed (shown by the green line), and a curve fit for vehicle speed (shown by the red line). Steady state speed corresponding to 900 RPM was determined by first clipping the data set to remove stationary (vehicle held at rest) and transient (vehicle accelerating form rest) data. The slope of the linear fit provided the approximate steady state speed for 900 RPM. Figure (b) vehicle speed versus time (shown by the blue line) and vehicle steady state speed (shown by the red line). Vehicle speed as a function of time was determined using Equation 3.3 and vehicle steady state speed was determined using the linear regression. Finally, Figure (c) shows the vehicle speed versus position (shown by the blue line) and vehicle steady state speed (shown by the red line). Vehicle speed as a function of position was determined using Equations 3.3 and 3.7.



(a) vehicle position as a function of time



(b) vehicle speed as a function of time



(c) vehicle speed as a function of position

Figure 3.4. Speed Calibration Results for 900 that Provide Position versus Time, Speed versus Time, and Speed versus Position.

The steady state vehicle speed corresponding to 900 RPM was determined by averaging three vehicle speeds for the last two seconds provided in the plot of vehicle speed versus time. Table 3.1 shows these three speeds. Error for the steady state speed was determined by calculating the 95% confidence interval. The steady state speed corresponding to 900 RPM is 0.62 ± 0.03 m/s (2.028 ± 0.1 ft/s). The plot of vehicle speed versus position was used to find the approximate vehicle speed at different distances along the tank.

Table 3.1. Vehicle Speed and Time Data Points Averaged to Find Steady State Vehicle Speed Corresponding to 900 RPM of the REMUS 100.

Time (s)	Vehicle Speed (m/s)
15	0.6254
14	0.6187
13	0.6102

3.2.5 Vehicle Speed Calibration Results

Steady state vehicle speed was evaluated for the RPM range of 600 to 1700. Figure 3.5 shows the speed calibration curve for the REMUS vehicle when attached to the moving carriage assembly.

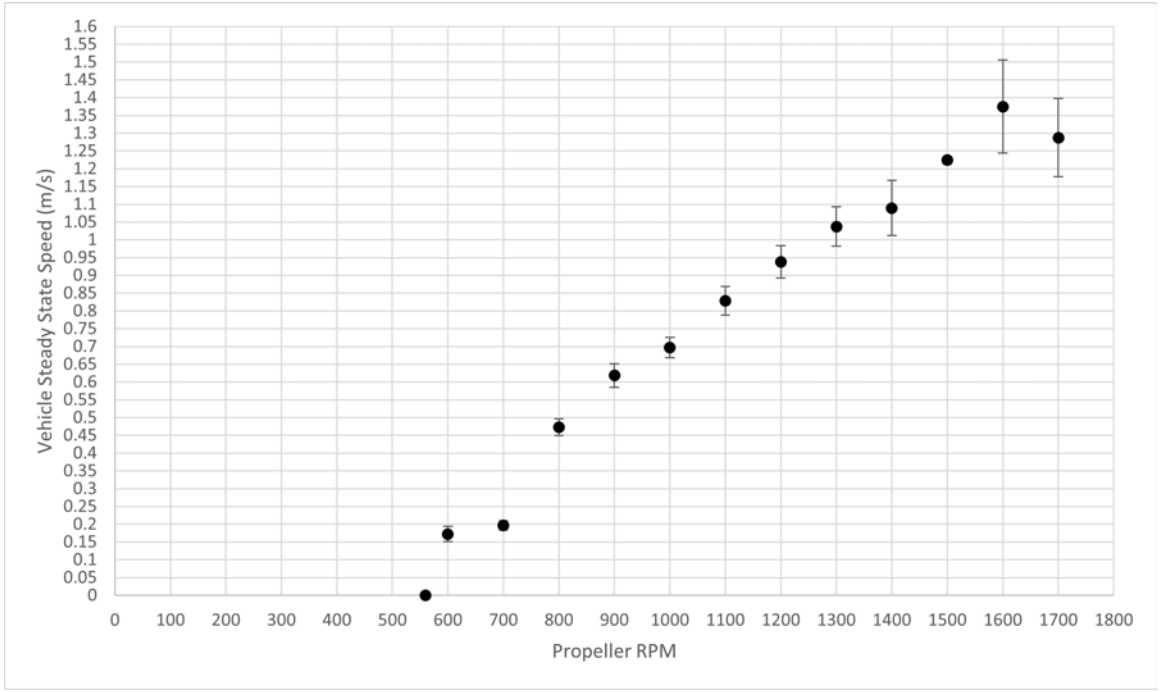


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Figure 3.5. REMUS 100 and Test Fixture System Steady State Speed Calibration Curve.

Table 3.2 summarizes the steady state vehicle speeds corresponding to the range of RPMs tested (600 to 1700 RPM).

Table 3.2. Propeller RPM and Steady State Speed of the REMUS 100 when Installed on the Test Fixture.

Propeller RPM	**Vehicle Speed (m/s)**
560	0
600	0.17 ± 0.02
700	0.20 ± 0.01
800	0.47 ± 0.02
900	0.62 ± 0.03
1000	0.70 ± 0.03
1100	0.83 ± 0.04
1200	0.94 ± 0.05
1300	1.04 ± 0.05
1400	1.09 ± 0.08
1500	1.22 ± 0.01
1600	1.37 ± 0.13
1700	1.29 ± 0.11

Initially, three different vehicle steady state speeds (low, medium, and high) were used during testing to evaluate the impact of speed on entanglement. The three [propeller RPM, steady state speeds] used were [600 RPM, 0.17 ± 0.02 m/s], [900 RPM, 0.62 ± 0.03 m/s], and [1200 RPM, 0.94 ± 0.05 m/s].

3.3 Marine Vegetation Characterization

A marine vegetation characterization was conducted for the synthetic giant kelp and synthetic eelgrass plants. Dimensional and material properties for each plant type were measured.

3.3.1 Giant Kelp Characterization

A kelp characterization was conducted by comparing dimensional and material properties of the synthetic giant kelp to a single representative piece of real giant kelp, shown in Figure 3.6. The real giant kelp strand used had been washed ashore on the beach in Monterey Bay, California.

Figure 3.6. Single Representative Piece of Real Giant Kelp from a Beach in Monterey Bay, CA.

3.3.2 Synthetic Giant Kelp Characterization Setup

Physical and material properties measured for the synthetic giant kelp and real giant kelp samples were stipe length, stipe diameter, number of blades per inch of length, blade length, blade width, density, buoyant ratio, deflection, and wrap-ability.

The plant length, blade length, and blade width were measured using a Westcott ruler that has an accuracy of 0.16 centimeters (1/16 inches) and the stipe diameter was measured using

Blackbolt vernier calipers that have an accuracy of 0.03 centimeters (1/128 inches). Figure 3.7 shows the Westcott ruler and Blackbolt calipers used for dimensional measurements.

Figure 3.7. Westcott Ruler and Blackbolt Calipers Used for Dimensional Measurements.

Figure 3.8 shows the equipment used to determine the density of each plant sample. The mass, m, of each sample was measured using a OHAUS Corporation Model SPX222 scale. Next, the graduated cylinder was filled with 2200 milliliters of fresh water. The plant sample volume, V, was determined by measuring the volume of fresh water displaced when each plant was submerged in the graduated cylinder filled with fresh water.

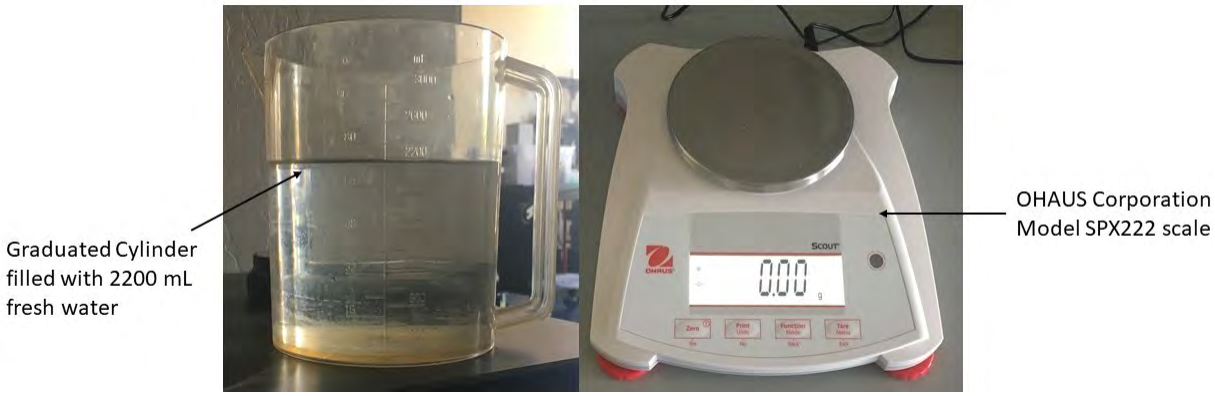


Figure 3.8. Equipment Used to Determine Density of the Synthetic and Real Giant Kelp Samples.

After measuring the mass and volume displaced, the density of each sample was calculated using Equation 3.8.

$$\rho = \frac{m}{V} \tag{3.8}$$

A buoyant ratio for each sample was then calculated using Equation 3.9 to account for the normal operating environment for each giant kelp sample. The operating environment for real giant kelp is seawater, which has a ρ of 1.025 g/mL at 15 degrees Celsius, and the operating environment for the synthetic giant kelp is freshwater, which has a ρ of 0.99913 g/mL at 15 degrees Celsius [30].

$$\text{Buoyant Ratio} = \frac{\rho_{\text{measured}}}{\rho_{\text{operating environment}}} \tag{3.9}$$

The rigidity of each sample was determined by measuring the deflection, δ, of each sample's stipe under its own weight when cantilevered. This deflection is similar to that of a cantilever beam with a uniform distributed load. This case of beam deflection depends on the weight of the beam, w, length of the beam, L, Young's Modulus, E, and the moment of inertia, I as shown by Equation 3.10. The quantity EI shown in Equation 3.10 measures a material's flexural rigidity or its resistance to bending [31].

$$\delta = \frac{wL^4}{8EI} \tag{3.10}$$

Figure 3.9 shows the experimental setup used to determine the stipe deflection for the synthetic and real kelp samples. Each sample was placed on an elevated flat surface. One end of the sample was fixed to the edge of the flat surface using tape. Varying lengths of the sample from 2.54 to 30.48 centimeters in 2.54-centimeter increments (1 to 12 inches in 1-inch increments) were suspended from the edge of the flat surface. The deflection was

determined by measuring the vertical distance between the fixed end and free end of the sample using a straight edge and the ruler.

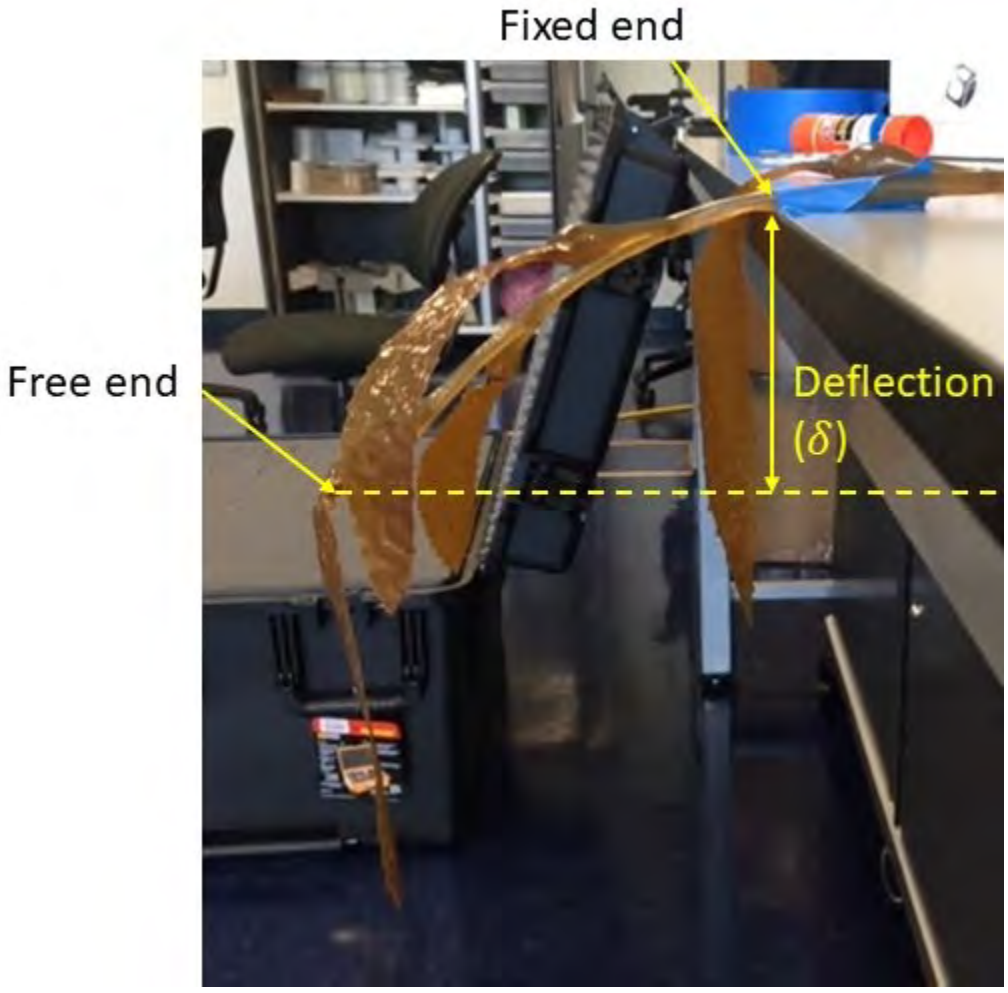


Figure 3.9. Experimental Setup Used to Measure the Deflection of the Synthetic and Real Giant Kelp Samples.

As an extension to the deflection properties, the wrap-ability of the synthetic and real kelp samples was measured. This was done by wrapping the stipe of each sample around cylinders of decreasing diameters. Diameters of particular interest were the REMUS 100 propeller hub diameter of 2.22 ± 0.03 centimeters (7/8 ± 1/128 inches) and the REMUS

blade tip diameter of 11.43 ± 0.03 centimeters (4.5 ± 1/128 inches). The diameter was decreased until the samples could no longer be wound around the cylinder.

3.3.3 Synthetic Giant Kelp Characterization Results

Table 3.3 shows the dimensional properties, density, and buoyant ratio for the synthetic and real giant kelp samples. No effort was made to characterize the entire giant kelp population; properties of the synthetic giant kelp sample were compared to the properties of the single representative piece of real giant kelp.

Table 3.3. Material Properties for the Single Representative Piece of Real Giant Kelp Sample and Synthetic Giant Kelp Sample.

Material Property	**Single Representative Piece of Real Giant Kelp**	**Synthetic Plastic Kelp**
Stipe Length	81.28 ± 0.2 cm	90.4875 ± 0.2 cm
Stipe Diameter	0.305 ± 0.03 cm	0.65 ± 0.03 cm
Blade Length	41.275 ± 0.2 cm	31.59125 ± 0.2 cm
Blade Width	10.95 ± 0.2 cm	3.19 ± 0.2 cm
Number of Blades	18	10
Distance between Blades	4.60 ± 0.2 cm	10.95 ± 0.2 cm
No. of Blades per length	0.2215 blades/cm	0.1105 blades/cm
Mass	208.03 ± 0.01 grams	141.11 ± 0.01 grams
Volume Displaced	200 ± 14.3 mL	150 ± 14.3 mL
Density	1.04015	0.94073 g/mL
Buoyant Ratio	1.015	0.9415

Figure 3.10 shows the deflection for the synthetic and real giant kelp for a range of lengths from 2.54 to 30.48 centimeters in 2.54-centimeter increments (1 to 12 inches in 1-inch increments) suspended over the edge of a flat surface (see Appendix C for table and supplemental figures).

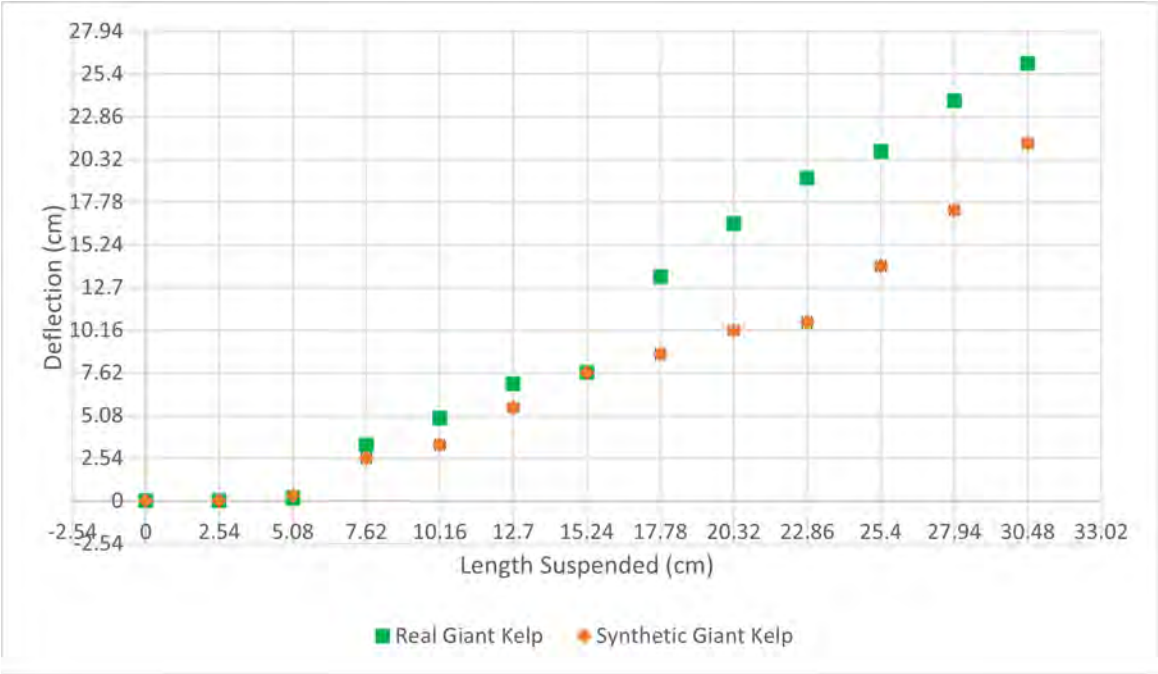


Figure 3.10. Deflection Results for the Real Giant Kelp and Synthetic Giant Kelp Samples.

The synthetic sample was able to be wrapped around a cylinder with a diameter of 3.02 ± 0.03 centimeters (1 and 3/16 ± 1/128 inches) and the real sample was able to be wrapped around a cylinder with a diameter of 2.22 ± 0.03 centimeters (7/8 ± 1/128 inches).

The synthetic giant kelp properties were compared to the real giant kelp properties using percent difference, calculated using Equation 3.11.

$$\% \text{ difference} = \frac{\text{synthetic} - \text{real}}{\text{real}} \times 100\% \tag{3.11}$$

Table 3.4 shows the percent difference between properties for the synthetic and real giant kelp samples. Major differences between the two samples were stipe diameter, distance between blades, and blades per inch. The stipe diameter of the synthetic sample was greater than the real sample, which may result in less material flexibility for the synthetic sample. Additionally, the difference in wrap-ability diameter suggests that it is less likely that the

synthetic giant kelp stipe will wrap around the vehicle's propeller shaft than a real giant kelp stipe, potentially resulting in a decreased likelihood of entanglement when operating in the synthetic giant kelp. The real sample was more densely populated with blades than the synthetic sample indicating that the canopy effect observed in real-world kelp forests may be limited in experimental tests using the synthetic giant kelp. When entering a vegetation field, it is expected that the REMUS speed will decrease. Since the synthetic giant kelp is less dense than real giant kelp, it is expected that the decrease in REMUS speed will not be as significant as it would in a real-world littoral environment. This would result in the vehicle traversing the entire vegetation field in a shorter time period, decreasing the time available for entanglement; this may result in a decreased likelihood of entanglement when operating in synthetic giant kelp.

Table 3.4. Percent Difference for the Material Properties of the Single Representative Piece of Real Giant Kelp and the Synthetic Giant Kelp.

Material Property	**Percent Difference**
Stipe Diameter	113%
Blade Length	-23.46%
Blade Width	-70.87%
Distance between Blades	138%
Number of Blades per cm	-50.1%
Buoyant Ratio	-7.24%
Wrap-ability Diameter	35.71%

Table 3.5 shows the percent difference for the deflection properties of the real and synthetic giant kelp samples. Overall, the real kelp sample exhibited greater deflection than the synthetic kelp sample. This indicates that the synthetic kelp sample is more rigid than the real kelp sample. Rigidity may impact the means of propeller entanglement and the likelihood that the vegetation will wrap around the propeller hub.

Table 3.5. Percent Difference for the Deflection of the Single Representative Piece of Giant Kelp and Synthetic Giant Kelp.

Length Suspended	Percent Difference
2.54 cm (1 in)	0%
5.08 cm (2 in)	100%
7.62 cm (3 in)	-23.81%
10.16 cm (4 in)	-32.26%
12.7 cm (5 in)	-20.45%
15.24 cm (6 in)	0%
17.78 cm (7 in)	-34.52%
20.32 cm (8 in)	-38.46%
22.86 cm (9 in)	-44.63%
25.4 cm (10 in)	-32.82%
27.94 cm (11 in)	-27.33%
30.48 cm (12 in)	-18.29%

3.3.4 Synthetic Eelgrass Characterization

A comparison between a real eelgrass plant and the synthetic eelgrass plant was not conducted because a real eelgrass sample was not available. However, similar physical and material properties of the synthetic eelgrass were measured using the same materials and methods used in the giant kelp characterization. Eelgrass properties measured were number of blades, blade length, blade width, density, buoyant ratio, deflection, and wrap-ability.

3.3.5 Synthetic Eelgrass Characterization Results

Table 3.6 shows the dimensional properties, density, and buoyant ratio measured for the synthetic eelgrass sample.

Table 3.6. Material Properties for the Synthetic Eelgrass Sample.

Material Property	Synthetic Eelgrass
Number of Blades	30
Blade Length	91.44 ± 0.2 cm
Blade Width	0.555625 ± 0.03 cm
Blade Thickness	0.0396875 ± 0.03 cm
Mass	37.68 ± 0.01 grams
Volume Displaced	57.2 ± 14.3 mL
Density	0.6587 g/mL
Buoyant Ratio	0.686

Table 3.7 shows the deflection measured for the synthetic eelgrass for a range of lengths from 2.54 to 15.24 centimeters in 2.54-centimeter increments (1 to 6 inches in 1-inch increments) when cantilevered (see Appendix C for supplemental figures). At 15.24 centimeters of suspended length, the eelgrass had no rigidity and hung vertically down; therefore, the deflection at larger suspended lengths for eelgrass were not measured.

Table 3.7. Deflection of the Synthetic Eelgrass Sample.

Length Suspended (cm)	Synthetic Eelgrass Deflection (cm)
2.54 ± 0.2	no deflection
5.08 ± 0.2	0.635 ± 0.2
7.62 ± 0.2	3.81 ± 0.2
10.16 ± 0.2	7.62 ± 0.2
12.7 ± 0.2	10.795 ± 0.2
15.24 ± 0.2	15.24 ± 0.2

Figure 3.11 shows the synthetic eelgrass sample wrapped around the smallest diameter cylinder achievable. The synthetic sample was able to be wrapped around a cylinder with a diameter of 0.8 ± 0.03 centimeters (5/16 ± 1/128 inches), which is smaller than the diameter of the REMUS propeller hub, 2.22 ± 0.03 centimeters (7/8 ± 1/128 inches).

Figure 3.11. Eelgrass Sample Wrapped around a 0.8 ± 0.03 cm Diameter Cylinder.

3.4 Chapter Summary

This chapter discussed the vehicle speed calibration conducted to determine the relationship between steady state speed and propeller RPM and to determine vehicle speed as a function of position for a propeller RPM range of 600 to 1200. Additionally, a marine vegetation characterization was conducted for the synthetic giant kelp and eelgrass samples used to simulate a littoral environment in the tow tank. The next chapter will discuss experimental testing procedures and the design of experiments for entanglement testing.

CHAPTER 4:
Experimental Testing Procedures and Design of Experiments for Entanglement Testing

4.1 Chapter Introduction

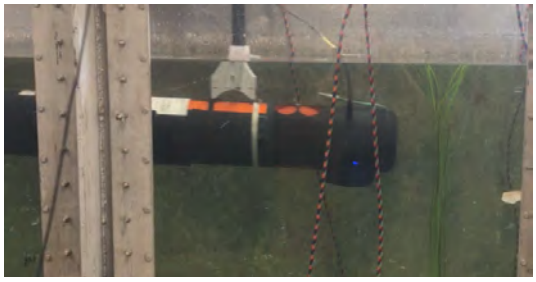
An experimental approach was used to evaluate the entanglement for the REMUS UUV propelled by an open, three-bladed propeller when operating in giant kelp and eelgrass vegetation. During testing, the REMUS navigated down the tow tank populated with different giant kelp and eelgrass configurations at a constant RPM, depth, and heading. Three different entanglement tests were conducted: a vegetation density and constant speed test, a lateral placement test, and an accelerating speed test. In the vegetation density and constant speed test, the density of giant kelp and eelgrass was varied using the marine vegetation configuration plate and the vehicle was provided enough distance before entrance into the vegetation field to reach its steady state speed which was varied across runs by changing the propeller RPM. In the lateral placement test, the eelgrass and giant kelp position was offset different distances from the center line of the vehicle. In the accelerating speed test, the propeller entrance speed to an eelgrass field was varied by providing the vehicle a limited distance to accelerate up to speed and thus resulted in the vehicle not being at its steady state speed when it passed through the vegetation field. Visual inspection was used to determine whether no entanglement, an entanglement event, or an entanglement kill occurred for each condition tested. Data was collected using data sheets generated in Excel. Additionally, the camera application on an iPhone 6s was used to collect video for each test condition.

4.2 Entanglement Definitions

For each of the three tests, visual inspection was used to determine whether an entanglement occurred. Possible entanglement results were No Entanglement, Entanglement Event, and Entanglement Kill. Major stages of each run considered were REMUS approach and entrance into the vegetation field, the propeller entrance and travel through the vegetation field, and the propeller exit.

4.2.1 No Entanglement

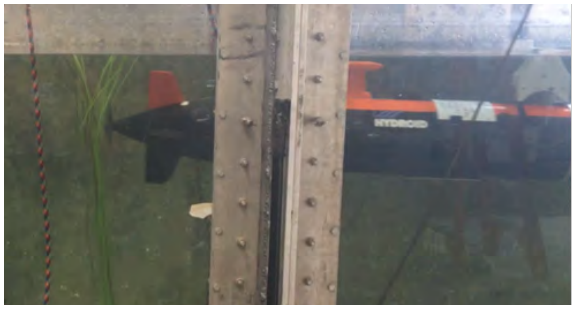
For a No Entanglement condition, marine vegetation wrapping of the propeller blades and hub, if any, does not noticeably slow down or stop the vehicle. Figure 4.1 shows a No Entanglement run. Figures (a) and (b) show the vehicle approach and entrance to the vegetation field at a steady state speed ($v \leftrightarrow$). Figures (c) and (d) show the propeller entrance and exit from the vegetation field; there is no noticeable change in speed and or vehicle motion ($v \leftrightarrow$). Figure (e) shows the remainder of the run, during which the vehicle remains at its steady state speed ($v \leftrightarrow$), resulting in a No Entanglement condition.



(a) vehicle approach ($v \leftrightarrow$)

(b) vehicle entrance ($v \leftrightarrow$)

(c) propeller entrance ($v \leftrightarrow$)



(d) propeller exit ($v \leftrightarrow$)

(e) no entanglement ($v \leftrightarrow$)

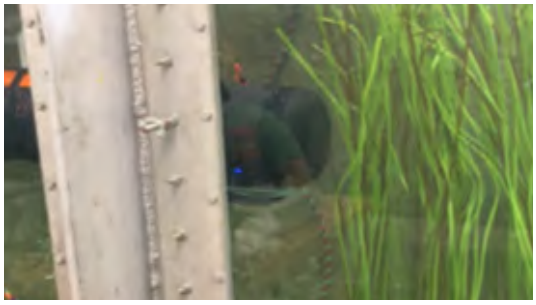
Figure 4.1. No Entanglement Run Example.

4.2.2 Entanglement Event

For an Entanglement Event condition, marine vegetation wraps around the propeller blades and or hub and causes a noticeable decrease in vehicle motion along the tank but does not completely stop the vehicle. Figure 4.2 shows an Entanglement Event run. Figures (a) and (b) show the vehicle approach to and entrance into the vegetation field at a steady state speed ($v \leftrightarrow$). When the propeller enters the vegetation field, as shown in Figure (c), vegetation begins to wrap around the propeller hub, as shown in Figure (d). The vehicle speed remains at its steady state value during this portion of the run ($v \leftrightarrow$). Propeller wrapping continues, as shown in Figures (e) and (f), causing vehicle speed to decrease ($v \downarrow$), indicating an entanglement. As the REMUS continues moving through the vegetation field at a lower, constant speed ($v \leftrightarrow$), the vegetation begins to unwrap from the propeller, as shown in Figure (g). Once the propeller is free from the vegetation, the vehicle exits the vegetation field, as shown in Figure (h).

4.2.3 Entanglement Kill

For an Entanglement Kill condition, marine vegetation wraps around the propeller blades and or hub and stops vehicle motion along the tank. Figure 4.3 shows an Entanglement Kill run. As the propeller enters the vegetation field, as shown in Figure (a), initial vegetation wrapping of the propeller hub occurs, as shown in Figure (b). The vehicle remains at a constant, steady state speed for this portion of the run ($v \leftrightarrow$). As shown in Figures (c) and (d), propeller wrapping continues as the vehicle travels farther into the vegetation field; wrapping is sufficient to entangle the vehicle and causes the vehicle speed to decrease ($v \downarrow$). Vegetation wrapping of the propeller hub continues as shown in Figure (e), causing further propeller entanglement that results in the REMUS becoming stuck in the vegetation field and the vehicle speed to decrease to zero (v= 0).



(a) vehicle approach ($v \leftrightarrow$)

(b) vehicle entrance ($v \leftrightarrow$)

(c) propeller entrance ($v \leftrightarrow$)

(d) initial propeller wrapping ($v \leftrightarrow$)

(e) propeller wrapping ($v \downarrow$)

(f) entanglement ($v \downarrow$)

(g) propeller unwrapping ($v \leftrightarrow$)

(h) propeller exit ($v \uparrow$)

Figure 4.2. Entanglement Event Run Example.

(a) propeller entrance ($v \leftrightarrow$)

(b) initial propeller wrapping ($v \leftrightarrow$)

(c) propeller wrapping ($v \downarrow$)

(d) entanglement ($v \downarrow$)

(e) entanglement kill ($v = 0$)

Figure 4.3. Entanglement Kill Run Example.

4.3 Vegetation Density and Constant Speed Entanglement Test

The vegetation density and constant speed test was conducted to determine the risk of entanglement for a range of vehicle speeds and vegetation densities. Tests were conducted for a range of vehicle speeds; vehicle speed was changed by changing the propeller RPM. A range between 600 to 1200 RPM in the forward and astern direction was used for testing. Giant kelp and eelgrass density was changed using the marine vegetation configuration plate. Different vegetation concentrations considered for testing were single density, low density, medium density, and high density configurations.

4.3.1 Vegetation Density and Constant Speed Entanglement Test Experimental Setup

Figure 4.4 shows the vegetation density and constant speed entanglement test setup. The REMUS was attached to the test fixture via a vertical sting. Next, different configurations of giant kelp and eelgrass were populated on the marine vegetation configuration plate. Using the lifting ropes, the marine vegetation configuration plate was lowered to the bottom of the tow tank and centered. A 20-pound weight was placed on top of the marine vegetation configuration plate to fix its position during tests. The lifting ropes were pulled to the edges of the tow tank to ensure that they did not interfere with the REMUS or the test fixture while conducting tests.

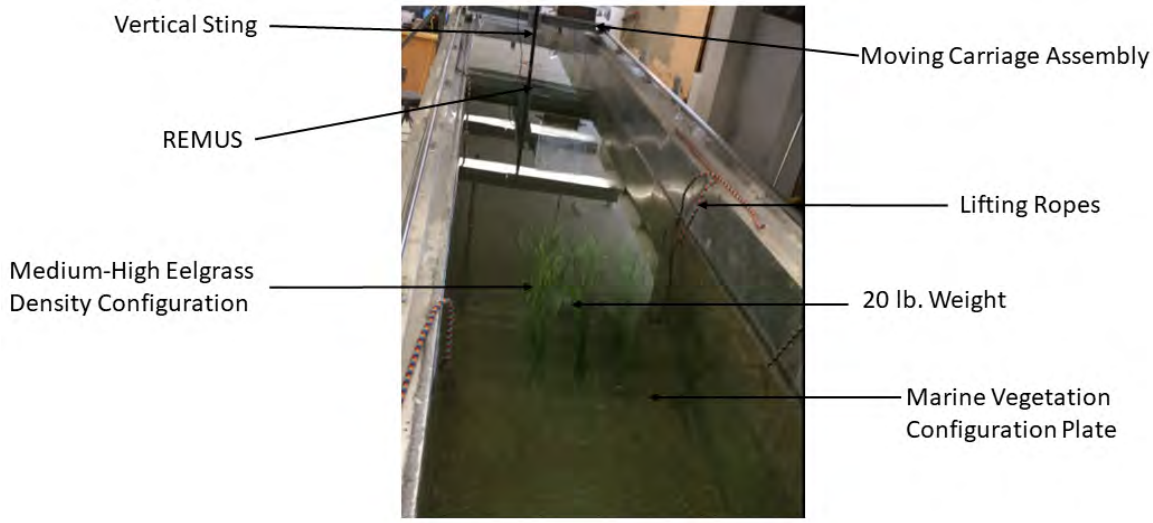


Figure 4.4. Vegetation Density and Constant Speed Entanglement Test Setup.

Giant kelp density was increased by decreasing the spacing between plants in 15.24-centimeter (6-inch) intervals and increasing the number of plants while eelgrass density was increased by decreasing the spacing between plants in 7.62-centimeter (3-inch) intervals and increasing the number of plants. Four different density configurations were tested for both eelgrass and giant kelp, as shown in Table 4.1. Figures 4.5 and 4.6 show the placement of giant kelp and eelgrass plants on the marine vegetation configuration plate used for each of the described configurations. Giant kelp plant placement is marked by a blue circle and eelgrass placement is marked by a yellow circle.

Table 4.1. Marine Vegetation Configurations for Vegetation Density and Constant Speed Entanglement Test.

Configuration	**Plant Type**	**Number of Plants**	**Density** $(plants/m^2)$	**Plant Spacing**
High Density	Giant Kelp	20	71.76	15.24 cm (6 in)
Medium Density	Giant Kelp	6	21.53	30.48 cm (12 in)
Low Density	Giant Kelp	4	14.35	45.72 cm (18 in)
Single Density	Giant Kelp	1	3.59	center line
High Density	Eelgrass	30	258.33	7.62 cm (3 in)
Medium Density	Eelgrass	9	77.50	15.24 cm (6 in)
Low Density	Eelgrass	4	34.44	22.86 cm (9 in)
Single Density	Eelgrass	1	8.61	Center line

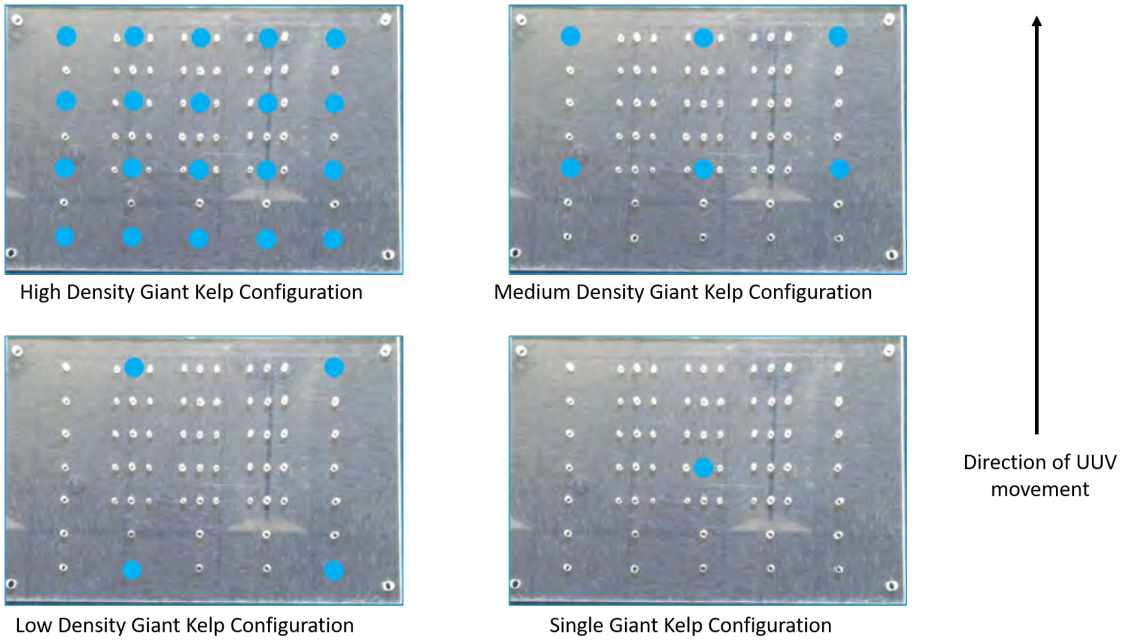


Figure 4.5. Giant Kelp Placement on the Marine Vegetation Configuration Plate for the Vegetation Density and Constant Speed Entanglement Test.

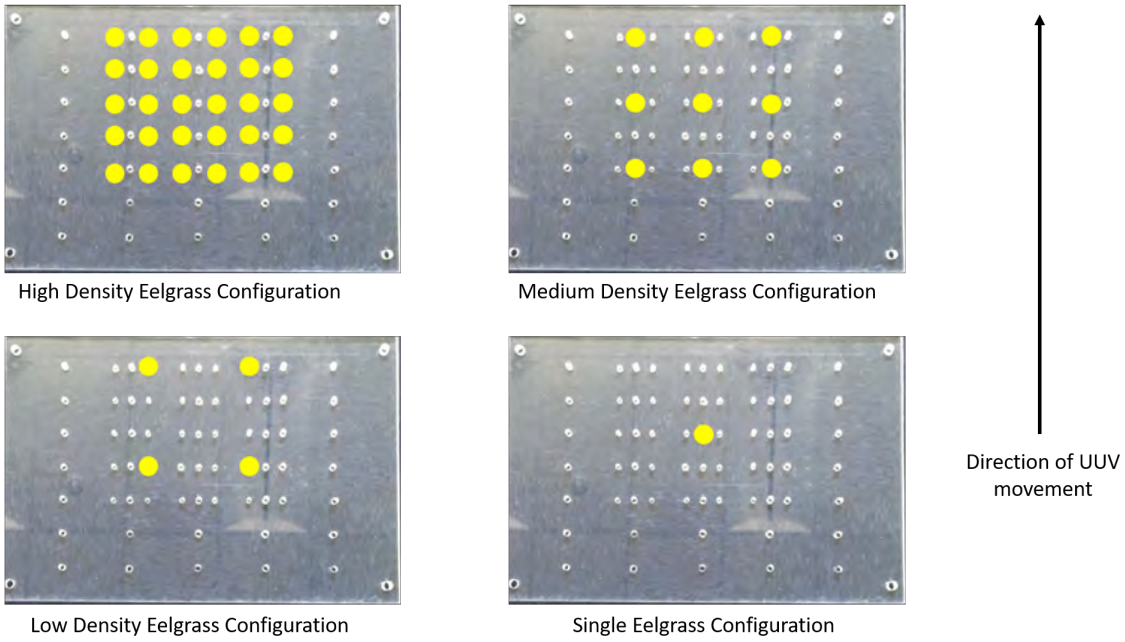


Figure 4.6. Eelgrass Placement on the Marine Vegetation Configuration Plate for the Vegetation Density and Constant Speed Entanglement Test.

The spacing, or density, of giant kelp in nature is dependent on various environmental conditions including water temperature, available nutrients and sun light, wave action, substrate strength, and predator population (i.e., sea urchins) [32]. Therefore, there is not a standard value to use as a reference to design the experiments against. Similarly, eelgrass density is dependent on environmental conditions to include water temperature, fish and invertebrate presence, availability of sun light, and the extent of coastal development [33]. 7.62-centimeter (3-inch) and 15.24-centimeter (6-inch) spacing intervals were selected to allow for a symmetrical vegetation configuration change with respect to the tow tank and REMUS center line. Additionally, these spacing intervals simulated the canopy effect seen in giant kelp forests and the meadow-like growth pattern exhibited by eelgrass to the best extent possible with available synthetic marine vegetation resources (20 giant kelp plants and 30 eelgrass plants).

4.3.2 Vegetation Density and Constant Speed Entanglement Test Data Collection Process

Initially, a 2 (marine vegetation type) x 4 (marine density configurations) x 3 (vehicle speeds) x 2 (propulsion directions) x 3 (trials) design was used for the vegetation density and constant speed test. The two marine vegetation types used were giant kelp and eelgrass. The four different marine vegetation density configurations considered were high, medium, low, and single. Three vehicle steady state speeds were tested: [600 RPM, 0.17 m/s], [900 RPM, 0.62 m/s], and [1200 RPM, 0.94 m/s]. The REMUS was tested for two propulsion directions, forward (clockwise propeller rotation) and astern (counterclockwise propeller rotation). Three trials were conducted for each design point. The order of runs was not randomized based on time required to change vegetation and vehicle settings. A data sheet was used to annotate the entanglement result for each run; possible entanglement results were No Entanglement (N), Entanglement Event (E), or Entanglement Kill (K). The most likely entanglement scenario (high density, lowest vehicle speed) was conducted first for each vegetation type; if no entanglement occurred, it was assumed that entanglement would not occur in a lower density and/or higher speed configuration. Supplemental video was taken using the camera application on an iPhone 6s for each test condition. Figure 4.7 shows the test matrix for the initial vegetation density and constant speed entanglement test.

RunOrder	Vegetation Type	Vegetation Configuration	Propeller RPM	Trial 1	Trial 2	Trial 3
1	Eelgrass	High Density	600			
2	Eelgrass	High Density	900			
3	Eelgrass	High Density	1200			
4	Eelgrass	Medium Density	600			
5	Eelgrass	Medium Density	900			
6	Eelgrass	Medium Density	1200			
7	Eelgrass	Low Density	600			
8	Eelgrass	Low Density	900			
9	Eelgrass	Low Density	1200			
10	Eelgrass	Single	600			
11	Eelgrass	Single	900			
12	Eelgrass	Single	1200			
13	Giant Kelp	High Density	600			
14	Giant Kelp	High Density	900			
15	Giant Kelp	High Density	1200			
16	Giant Kelp	Medium Density	600			
17	Giant Kelp	Medium Density	900			
18	Giant Kelp	Medium Density	1200			
19	Giant Kelp	Low Density	600			
20	Giant Kelp	Low Density	900			
21	Giant Kelp	Low Density	1200			
22	Giant Kelp	Single	600			
23	Giant Kelp	Single	900			
24	Giant Kelp	Single	1200			

Figure 4.7. Initial Test Matrix for the Vegetation Density and Constant Speed Entanglement Test.

Results from this initial vegetation density and constant speed test were used to determine the speed at which entanglement began to occur for each density configuration (entanglement threshold). The highest speed, corresponding to the highest RPM, at which entanglement occurred for each density configuration was used as an initial testing point to find this threshold. RPM was increased incrementally by 100 RPM from this initial testing point until a RPM resulting in no entanglement was reached. Then, propeller RPM was incremented in 50 RPM increments to determine the entanglement threshold speed within 50 RPM.

4.3.3 Vegetation Density and Constant Speed Entanglement Testing Procedure

Following experimental setup, the REMUS was moved to the test start point by manually moving the carriage assembly. The moving carriage assembly was held stationary while the propeller RPM was increased to the test value using the REMUS VIP software. For the first trial of each test condition, a video was started. Once the test RPM was reached, the moving carriage assembly was released, allowing the REMUS to maneuver down the tow tank. An operator was stationed by the vegetation field to determine if no entanglement, an entanglement event, or an entanglement kill occurred. Propeller RPM was then reset to zero and the vehicle was disentangled, if required. The giant kelp or eelgrass configuration was changed as required. Prior to each test run, the marine vegetation field was straightened out, as shown in Figure 4.8, to counteract the disturbance effect that the REMUS had on the marine vegetation as it moved through it. This procedure was repeated until vegetation density and constant speed entanglement testing was completed.

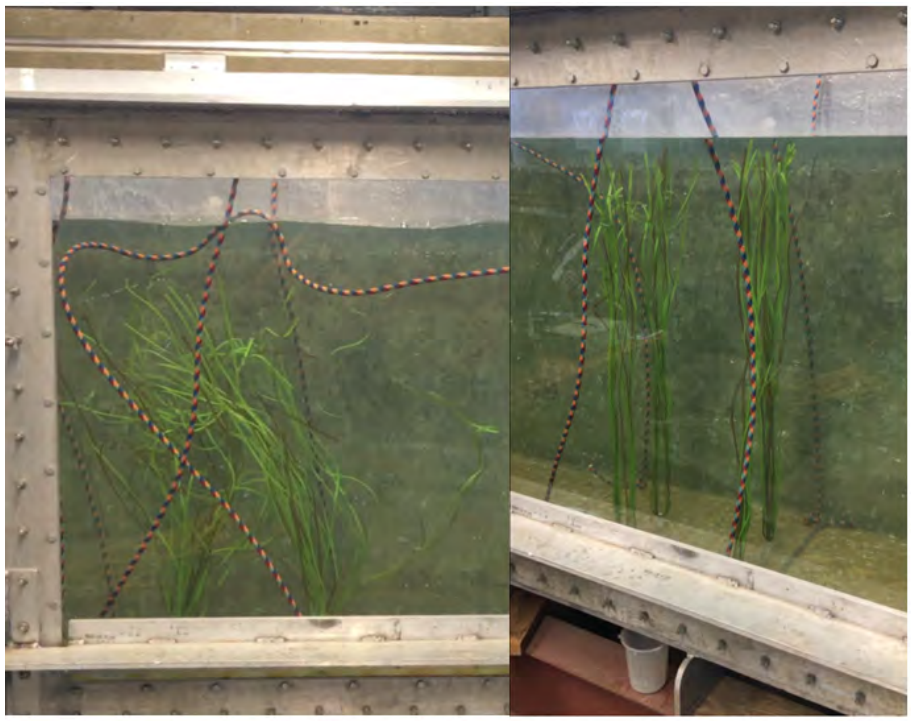


Figure 4.8. Marine Vegetation Field Reset prior to Additional Test Runs.

4.4 Lateral Placement Entanglement Test

The lateral placement test was conducted to determine the impact that marine vegetation location relative to the center line of the vehicle and its propeller had on entanglement. All tests were conducted at a steady state speed of [600 RPM, 0.17 m/s] with a single density vegetation concentration (one eelgrass or giant kelp plant). Vegetation placement was changed by moving the plant different distances left and right of the tow tank/vehicle center line.

4.4.1 Lateral Placement Entanglement Test Experimental Setup

The lateral placement test setup used was the same one used for the vegetation density and constant speed test with the exception of the marine vegetation configurations used. Table 4.2 shows the different configurations used for lateral placement entanglement testing. Figures 4.9 and 4.10 show the placement of giant kelp and eelgrass plants on the marine vegetation configuration plate used for each of the described configurations. Giant kelp plant placement is marked by a blue circle and eelgrass placement is marked by a yellow circle.

Table 4.2. Marine Vegetation Configurations for Lateral Placement Entanglement Testing.

Configuration	Plant Type	Plant Placement Relative to Tank Center line
1	Giant Kelp	15.24 cm (6 in), offset to port
2	Giant Kelp	30.48 cm (12 in), offset to port
3	Giant Kelp	15.24 cm (6 in), offset to starboard
4	Giant Kelp	30.48 cm (12 in), offset to starboard
5	Eelgrass	3.81 cm (1.5 in), offset to port
6	Eelgrass	11.43 cm (4.5 in), offset to port
7	Eelgrass	19.05 cm (7.5 in) offset to port
8	Eelgrass	3.81 cm (1.5 in), offset to starboard
9	Eelgrass	11.43 cm (4.5 in), offset to starboard
10	Eelgrass	19.05 cm (7.5 in), offset to starboard

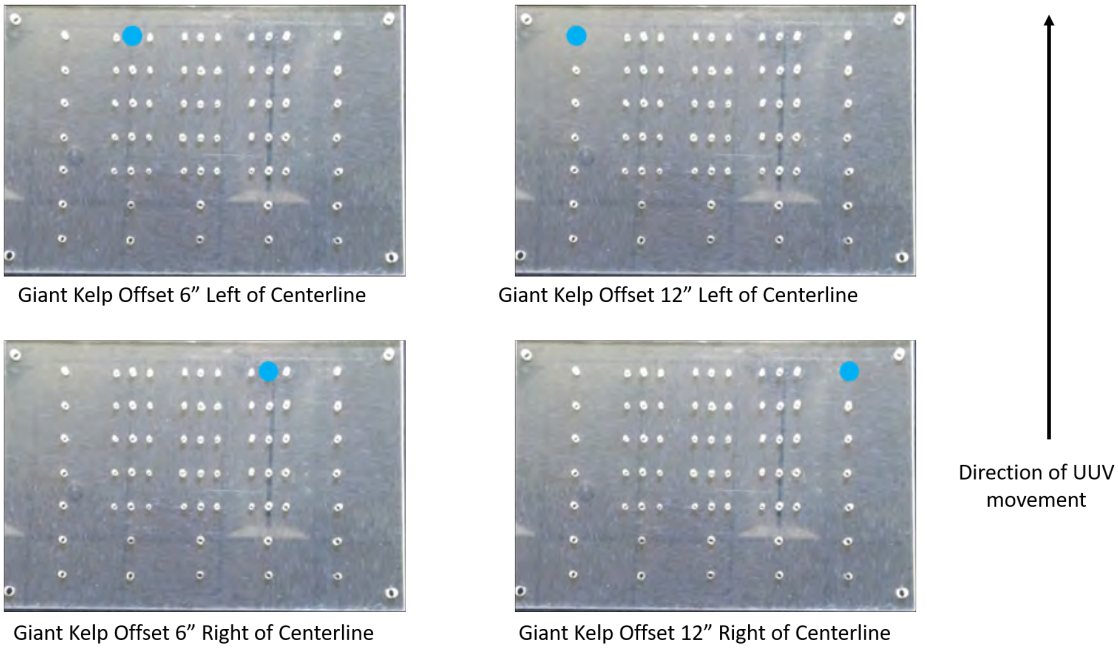


Figure 4.9. Giant Kelp Placement on the Marine Vegetation Configuration Plate for the Lateral Placement Entanglement Test.

Figure 4.10. Eelgrass Placement on the Marine Vegetation Configuration Plate for the Lateral Placement Entanglement Test.

4.4.2 Lateral Placement Entanglement Test Data Collection Process and Testing Procedure

A 6 (placement configuration) x 2 (propulsion directions) x 3 (trials) design was used for eelgrass placement testing and a 4 (placement configuration) x 2 (propulsion directions) x 3 (trials) was used for giant kelp placement testing. For the eelgrass placement testing, the six placement configurations used were one plant placed 3.81, 11.43, and 19.05 centimeters (1.5, 4.5, and 7.5 inches) to the left and right of the tank/vehicle center line. For the giant kelp placement testing, the 4 placement configurations used were 1 plant placed 15.24 and 30.48 centimeters (6 and 12 inches) to the left and right of the tank/vehicle center line. Tests were conducted for forward and astern propulsion. Three trials were conducted for each design point. Similar to the vegetation density and constant speed entanglement test, the order of runs was not randomized and a data sheet was used to annotate the entanglement result for each run. Supplemental video was taken using the camera application on an iPhone 6s for each test condition. Additionally, lateral placement entanglement testing followed the same testing procedure used for the vegetation density and constant speed entanglement testing. Figure 4.11 shows the test matrix for the lateral placement entanglement test.

RunOrder	Vegetation Type	Placement Configuration	Direction of Movement	Trial 1	Trial 2	Trial 3
1	Eelgrass	1.5", port	Forward			
2	Eelgrass	4.5", port	Forward			
3	Eelgrass	7.5" port	Forward			
4	Eelgrass	1.5", starboard	Forward			
5	Eelgrass	4.5", starboard	Forward			
6	Eelgrass	7.5", starboard	Forward			
7	Eelgrass	1.5", port	Astern			
8	Eelgrass	4.5", port	Astern			
9	Eelgrass	7.5" port	Astern			
10	Eelgrass	1.5", starboard	Astern			
11	Eelgrass	4.5", starboard	Astern			
12	Eelgrass	7.5", starboard	Astern			
13	Giant Kelp	6", port	Forward			
14	Giant Kelp	12" port	Forward			
15	Giant Kelp	6", starboard	Forward			
16	Giant Kelp	12", starboard	Forward			
17	Giant Kelp	6", port	Astern			
18	Giant Kelp	12" port	Astern			
19	Giant Kelp	6", starboard	Astern			
20	Giant Kelp	12", starboard	Astern			

Figure 4.11. Test Matrix for the Lateral Placement Entanglement Test.

4.5 Accelerating Speed Entanglement Test

In the vegetation density and constant speed test, the propeller RPM and vehicle speed were correlated. The accelerating speed test was conducted to decouple propeller RPM from vehicle speed to determine if propeller RPM or vehicle speed, individually, were important with respect to entanglement. This testing was done as a preliminary evaluation of the hypothesis that the likelihood of entanglement increases as the number of propeller revolutions over a given distance increases. The number of propeller revolutions over a given distance is provided by Equation 4.1.

$$\text{Propeller revolutions} = \frac{\text{RPM} \times \text{Characteristic Length}}{\text{Current Vehicle Speed}} \tag{4.1}$$

The vehicle speed at the time of the propeller entrance into a vegetation field was changed by varying the distance between the vehicle and the vegetation field at the run start. Five different distances were evaluated during this test. Runs were conducted for a range of propeller RPMs between 600 to 1200 in the forward direction. One eelgrass configuration was considered; the configuration used was seven eelgrass plants, center line, spaced 7.62 centimeters (3 inches) apart.

4.5.1 Accelerating Speed Entanglement Test Experimental Setup

Figure 4.12 shows the accelerating speed entanglement test experimental setup. The marine vegetation configuration plate was populated with seven eelgrass plants located center line and spaced 7.62 centimeters (3 inches) apart. Five different distances relative to the entrance of the vegetation field and propeller were marked in 30.48 ± 0.2 centimeter (1 foot ± 1/16 inch) intervals using blue painter's tape on the side of the tow tank.

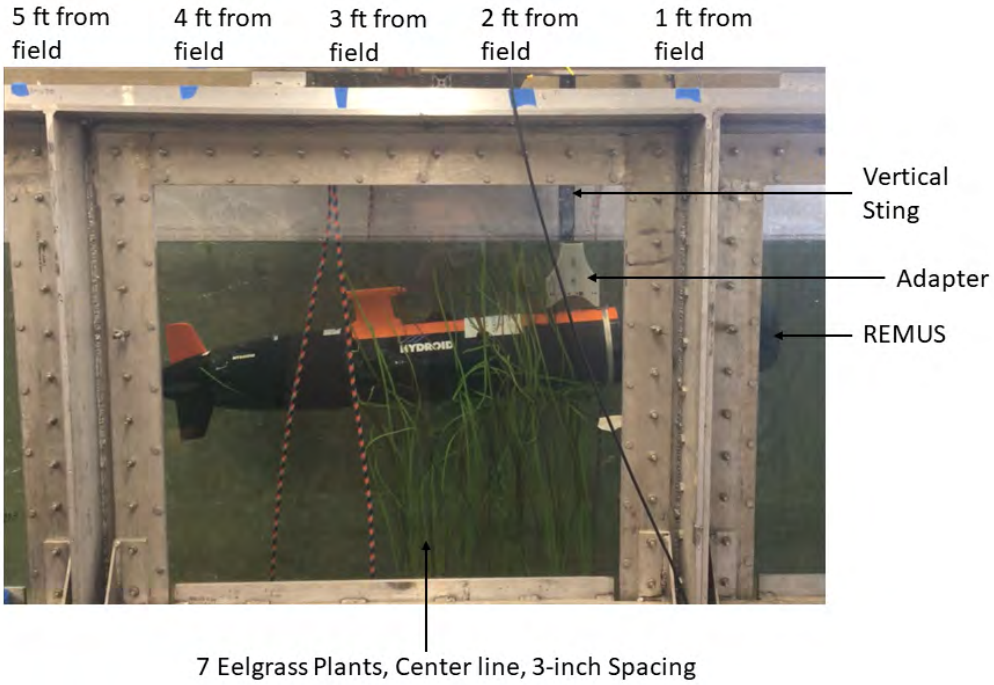


Figure 4.12. Accelerating Speed Entanglement Test Experimental Setup.

Figure 4.13 shows the placement of the eelgrass plants on the marine vegetation configuration plate (marked by yellow circles) used for the accelerating speed entanglement test.

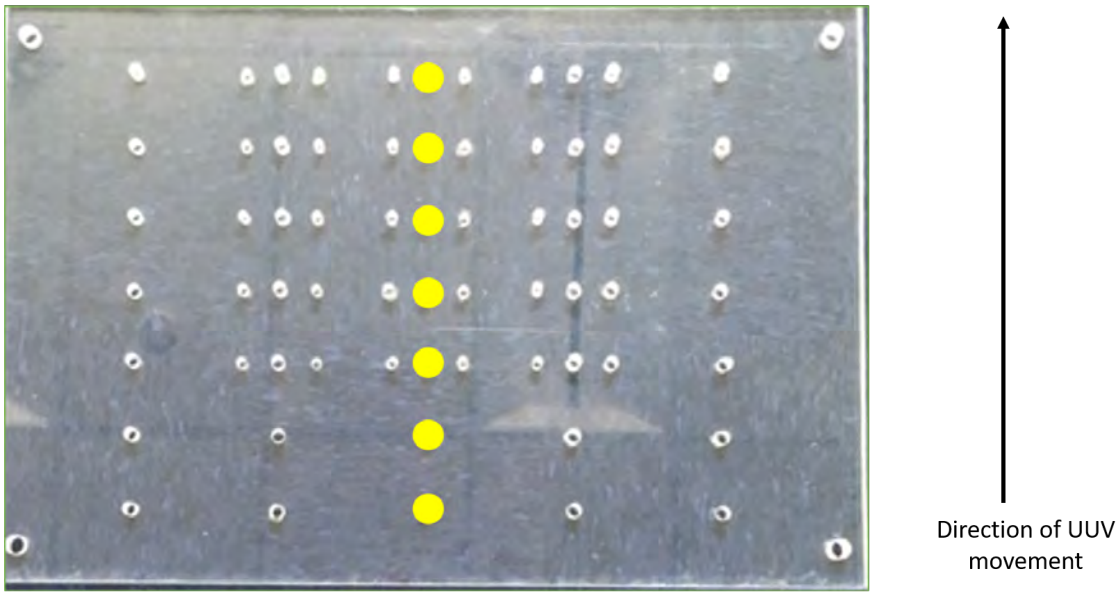


Figure 4.13. Eelgrass Placement on the Marine Vegetation Configuration Plate for the Accelerating Speed Entanglement Test.

4.5.2 Accelerating Speed Entanglement Test Data Collection Process

This test served as a preliminary analysis of the effect that vehicle speed has on entanglement when the propeller enters the vegetation field. Factors changed for each test point were propeller RPM and the distance between the propeller and front of the vegetation field. Tests were conducted for 600 to 1200 RPM in 100 RPM increments. Distances used were 1.525 ± 0.002, 1.22 ± 0.002, 0.915 ± 0.002, 0.61 ± 0.002, and 0.305 ± 0.002 meters (5 feet ± 1/16 inches , 4 feet ± 1/16 inches, 3 feet ± 1/16 inches, 2 feet ± 1/16 inches, 1 foot ± 1/16 inches). The most likely entanglement scenario was when the propeller started 0.305 ± 0.002 meters (1 foot ± 1/16 inches) from the vegetation field; if entanglement occurred prior to that start point, it was assumed that closer distances would entangle. Similar to the previous entanglement tests, the order of runs was not randomized and a data sheet was used to annotate the entanglement result for each run. Supplemental video was taken using the camera application on an iPhone 6s for each test condition. Figure 4.14 shows the test matrix for the accelerating speed entanglement test.

RunOrder	Propeller Distance from Vegetation Field (ft)	Propeller RPM	Trial 1	Trial 2	Trial 3
1	5	1200			
2	4	1200			
3	3	1200			
4	2	1200			
5	1	1200			
6	5	1100			
7	4	1100			
8	3	1100			
9	2	1100			
10	1	1100			
11	5	1000			
12	4	1000			
13	3	1000			
14	2	1000			
15	1	1000			
16	5	900			
17	4	900			
18	3	900			
19	2	900			
20	1	900			
21	5	800			
22	4	800			
23	3	800			
24	2	800			
25	1	800			
26	5	700			
27	4	700			
28	3	700			
29	2	700			
30	1	700			
31	5	600			
32	4	600			
33	3	600			
34	2	600			
35	1	600			

Figure 4.14. Test Matrix for the Accelerating Speed Placement Entanglement Test.

4.5.3 Accelerating Speed Entanglement Testing Procedure

The REMUS was moved to the test start point using the carriage assembly and aligning the front of the moving carriage assembly with the aft edge of the tape. Like in the previous tests,

the moving carriage assembly was held stationary while the propeller RPM was increased to the test value and released. Propeller RPM was reset to zero and the vehicle was disentangled if required. Prior to each test run, the blades of the eelgrass plants were straightened out to counteract the disturbance effect that the REMUS had on the marine vegetation as it moved through it. This procedure was repeated until the accelerating speed test was complete.

4.6 Chapter Summary

This chapter discussed the three entanglement tests conducted for the REMUS, propeller by an open, three-bladed propeller. Three different entanglement tests - vegetation density and constant speed, lateral placement, and accelerating speed - were conducted to evaluate entanglement conditions. Different conditions of entanglement were considered during testing: no entanglement, entanglement event, and entanglement kill. Data sheets and video were used to collect data during testing. The next chapter provides testing results and major findings.

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CHAPTER 5:
Results and Analysis

5.1 Chapter Introduction

This chapter provides the results and analysis for entanglement testing. The major findings are included for the vegetation density and constant speed, lateral placement, and accelerating speed entanglement tests. Risk was used to assess entanglement for different steady state speeds/propeller RPMs, vegetation type, and vegetation densities. The number of entanglements and video were used to evaluate propeller entanglement for different vegetation placements. A speed ratio and likelihood of entanglement were used to analyze the effect of propeller entrance speed into an eelgrass field on entanglement.

5.2 Vegetation Density and Constant Speed Entanglement Test

The vegetation density and constant speed test was conducted to determine the risk of entanglement for a range of vehicle speeds and vegetation densities.

5.2.1 Vegetation Density and Constant Speed Entanglement Test Results

Table 5.1 shows the initial vegetation density and constant speed entanglement test results for forward propulsion. In the table, a "K" corresponds to an entanglement kill, an "E" corresponds to an entanglement event, and a "N" corresponds to no entanglement. No entanglement observed for the most likely entanglement (high density, [600 RPM, 0.17 m/s]), indicated that entanglement would not occur in lower density and or higher speed configurations; this assumed no entanglement condition is annotated by "N*".

Table 5.1. Vegetation Density and Constant Speed Entanglement Test Results when Operating Forward Propulsion.

Vegetation Type	Vegetation Density	RPM	Steady State Speed (m/s)	Trial 1	Trial 2	Trial 3
Eelgrass	High	600 RPM	0.17	K	K	K
Eelgrass	High	900 RPM	0.62	K	E	K
Eelgrass	High	1200 RPM	0.94	N	N	N
Eelgrass	Medium	600 RPM	0.17	K	E	E
Eelgrass	Medium	900 RPM	0.62	N	N	N
Eelgrass	Medium	1200 RPM	0.94	N	N	N
Eelgrass	Low	600 RPM	0.17	N	N	N
Eelgrass	Low	900 RPM	0.62	N	N	N
Eelgrass	Low	1200 RPM	0.94	N	N	N
Eelgrass	Single	600 RPM	0.17	N	N	N
Eelgrass	Single	900 RPM	0.62	N	N	N
Eelgrass	Single	1200 RPM	0.94	N	N	N
Giant Kelp	High	600 RPM	0.17	N	N	N
Giant Kelp	High	900 RPM	0.62	N	N	N*
Giant Kelp	High	1200 RPM	0.94	N*	N*	N*
Giant Kelp	Medium	600 RPM	0.17	N*	N*	N*
Giant Kelp	Medium	900 RPM	0.62	N*	N*	N*
Giant Kelp	Medium	1200 RPM	0.94	N*	N*	N*
Giant Kelp	Low	600 RPM	0.17	N*	N*	N*
Giant Kelp	Low	900 RPM	0.62	N*	N*	N*
Giant Kelp	Low	1200 RPM	0.94	N*	N*	N*
Giant Kelp	Single	600 RPM	0.17	N*	N*	N*
Giant Kelp	Single	900 RPM	0.62	N*	N*	N*
Giant Kelp	Single	1200 RPM	0.94	N*	N*	N*

Table 5.2 shows the additional entanglement results for eelgrass when operating at additional RPM/speeds in the forward direction. Additional speeds were not tested using giant kelp based on previous no entanglement results when operating forward propulsion.

Table 5.2. Additional Vegetation Density and Constant Speed Entanglement Test Results for Eelgrass when Operating Forward Propulsion.

Vegetation Density	RPM	Trial 1	Trial 2	Trial 3
High	1000 RPM	K	K	K
High	1050 RPM	N	N	N
Medium	800 RPM	N	N	N
Medium	700 RPM	N	N	N
Medium	650 RPM	N	N	N
Low	650 RPM	N	N	N
Low	700 RPM	N	N	N
Single	650 RPM	N	N	N

Table 5.3 shows the vegetation density and constant speed entanglement test results for astern propulsion. The least likely entanglement scenario conditions (lower vegetation densities, and higher speeds) were tested first. Entanglement kills observed when operating 1200 RPM through a low density vegetation configuration indicated that an entanglement kill would occur for remaining higher density configurations and lower speed test runs (annotated by "K*").

Table 5.3. Vegetation Density and Constant Speed Entanglement Test Results when Operating Astern Propulsion.

Vegetation Type	Vegetation Density	RPM	Trial 1	Trial 2	Trial 3
Eelgrass	High	600 RPM	K*	K*	K*
Eelgrass	High	900 RPM	K*	K*	K*
Eelgrass	High	1200 RPM	K*	K*	K*
Eelgrass	Medium	600 RPM	K*	K*	K*
Eelgrass	Medium	900 RPM	K*	K*	K*
Eelgrass	Medium	1200 RPM	K*	K*	K*
Eelgrass	Low	600 RPM	K*	K*	K*
Eelgrass	Low	900 RPM	K	K	K
Eelgrass	Low	1200 RPM	K	K	K
Eelgrass	Single	600 RPM	K*	K*	K*
Eelgrass	Single	900 RPM	K	K	K
Eelgrass	Single	1200 RPM	E	E	E
Giant Kelp	High	600 RPM	E	E	E
Giant Kelp	High	900 RPM	E	E	E
Giant Kelp	High	1200 RPM	E	N	N
Giant Kelp	Medium	600 RPM	E	K	E
Giant Kelp	Medium	900 RPM	E	E	E
Giant Kelp	Medium	1200 RPM	N	E	N
Giant Kelp	Low	600 RPM	K	E	K
Giant Kelp	Low	900 RPM	N	N	E
Giant Kelp	Low	1200 RPM	N	N	N
Giant Kelp	Single	600 RPM	K	K	E
Giant Kelp	Single	900 RPM	E	K	N
Giant Kelp	Single	1200 RPM	N	N	N

Table 5.4 shows the additional entanglement results for giant kelp when operating at addi-

tional RPM/speeds in the astern direction. Additional speeds were not tested using eelgrass based on previous entanglement kill results when operating astern propulsion.

Table 5.4. Additional Vegetation Density and Constant Speed Entanglement Test Results for Giant Kelp when Operating Astern Propulsion.

Vegetation Density	RPM	Trial 1	Trial 2	Trial 3
High	1000 RPM	N	N	N
High	950 RPM	K	E	K
Medium	1000 RPM	N	N	N
Medium	950 RPM	N	N	N
Low	950 RPM	N	N	N
Low	800 RPM	E	N	N
Low	750 RPM	E	N	E
Low	700 RPM	N	E	K
Low	650 RPM	K	N	E
Single	650 RPM	N	K	N
Single	950 RPM	N	N	N

5.2.2 Vegetation Density and Constant Speed Entanglement Test Analysis

Entanglement conditions of an open three-bladed propeller for different marine vegetation types, different vegetation densities, and different vehicle speeds were evaluated in the vegetation density and constant speed entanglement testing. The different configurations tested were evaluated in terms of entanglement risk. Entanglement risk depends on the number of entanglement kills and entanglement events observed over three trials for each test configuration. Table 5.5 provides the five levels of risk used to classify the entanglement risk for each configuration.

Table 5.5. Entanglement Risk Ratings.

Risk Level	Description
Very High	3 Kills
High	3 Events OR 2 Events and 1 Kill OR 1 Event and 2 Kills
Moderate	2 Events and 0 Kills OR 1 Event and 1 Kill OR 0 Events and 1 Kill
Low	1 Event and 0 Kills
Minimal	0 Events and 0 Kills

Figure 5.1 shows the entanglement risks associated with the different conditions tested. Propeller RPM (indicative of vehicle speed), propulsion direction, vegetation type, and vegetation density were the different factors changed throughout the test. Results for tested configurations are annotated with "N" for no entanglement, "E" for entanglement event, and "K" for entanglement kill. For untested conditions, boundary condition results were used to determine the expected risk. For example, the entanglement risk for the REMUS operating forward propulsion in high density eelgrass was "Very High" for both [1000 RPM, 0.70 m/s] and [900 RPM, 0.62 m/s]; therefore, it was assumed that entanglement risk would be "Very High" for 950 RPM. For boundary conditions that are not the same, the higher level of entanglement risk was assumed. For example, the entanglement risk for the REMUS operating astern propulsion in high density giant kelp was "Low " for [1200 RPM, 0.94 m/s] but "Minimal" for [1000 RPM, 0.7 m/s]; therefore it was assumed that entanglement risk was "Low" for an operating range of 1050-1200 RPM. Major findings are detailed below.

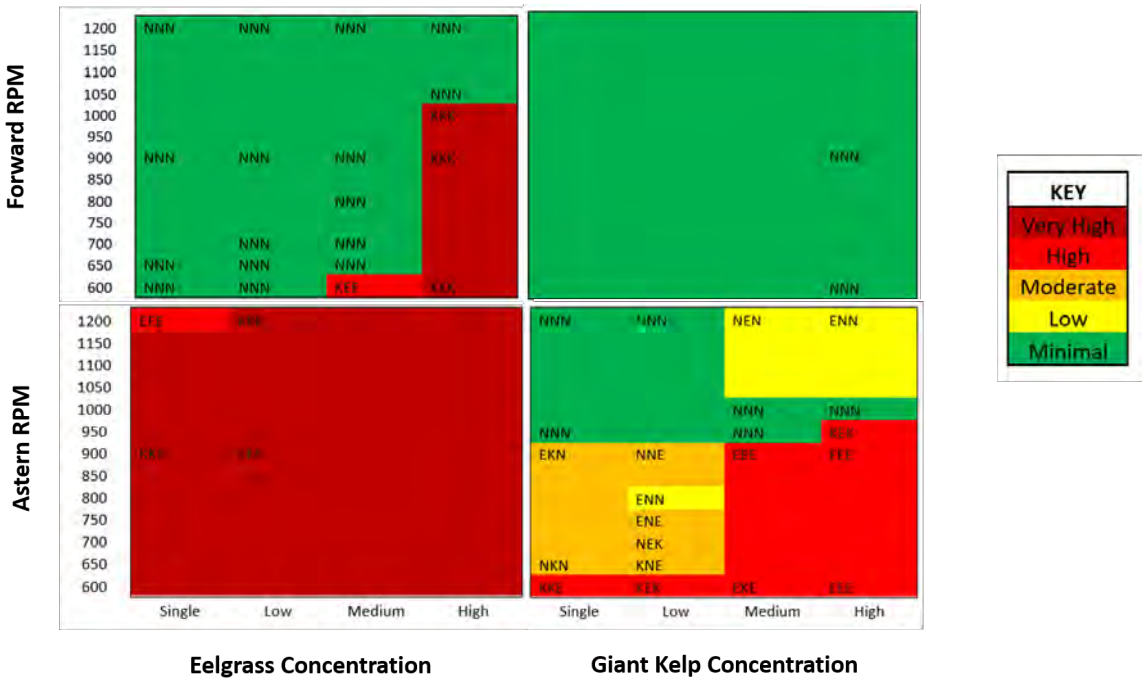


Figure 5.1. Entanglement Risk for the REMUS Operating in Different Densities of Giant Kelp and Eelgrass with a Propeller RPM Range of 600-1200 RPM.

Major Finding 1: Eelgrass Entanglement Risk Is Greater than Giant Kelp Entanglement Risk

As shown in Figure 5.1, eelgrass poses a greater entanglement risk than giant kelp for all configurations tested. In tests resulting in an entanglement event or entanglement kill, entanglement was a result of vegetation wrapping around the propeller hub and or blades. Figure 5.2 provides examples of giant kelp and eelgrass entanglement. Individual eelgrass blades wrapping around the propeller hub and propeller blades causes vehicle entanglement in eelgrass while the giant kelp stipe wrapping around the propeller hub causes vehicle entanglement in giant kelp.

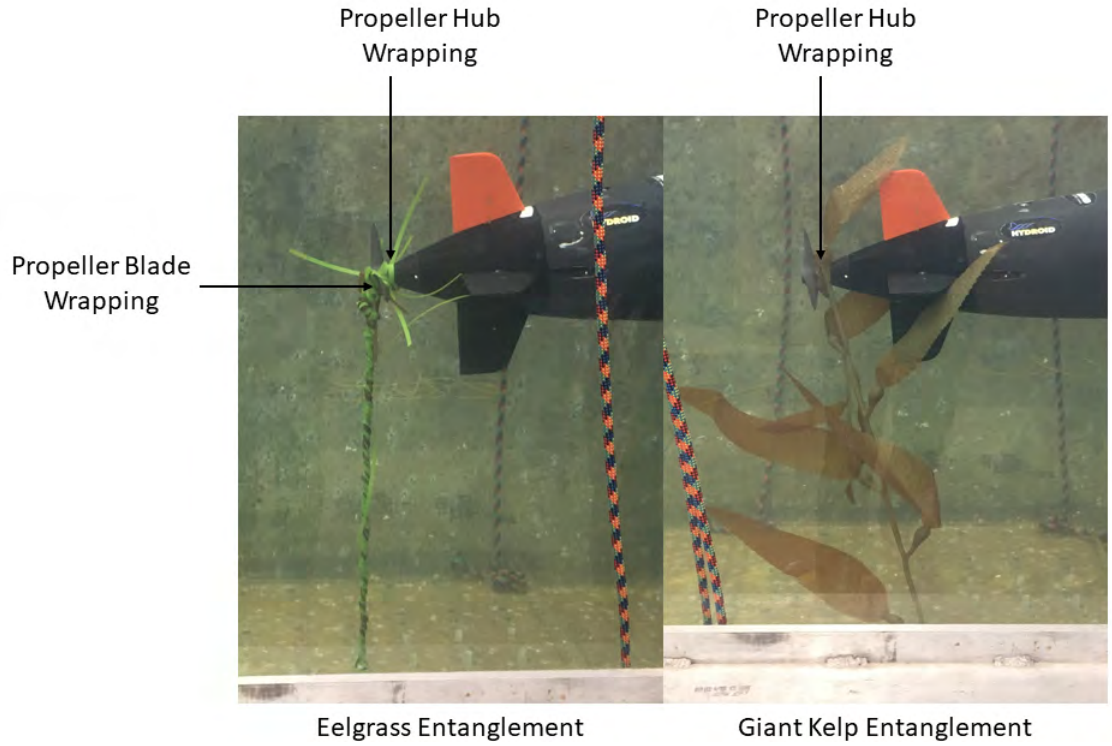


Figure 5.2. Eelgrass and Giant Kelp Propeller Wrapping Resulting in an Entanglement.

Eelgrass entanglement risk is greater than the giant kelp entanglement risk due to material differences between the two vegetation types. The wrap-ability and deflection properties discussed previously are the most significant. When compared to giant kelp, eelgrass has a larger deflection and smaller wrap-ability diameter. This means that it is able to bend and wrap around the propeller hub more easily than the giant kelp stipe. Another important material difference between the giant kelp and eelgrass is that each giant kelp plant used had one stipe while each eelgrass plant used had thirty blades. As shown in Figure 5.3, one eelgrass blade wrapped around the propeller can cause entanglement. Therefore, one eelgrass plant has thirty entanglement opportunities (one for each blade) while one giant kelp has one entanglement opportunity (the stipe).

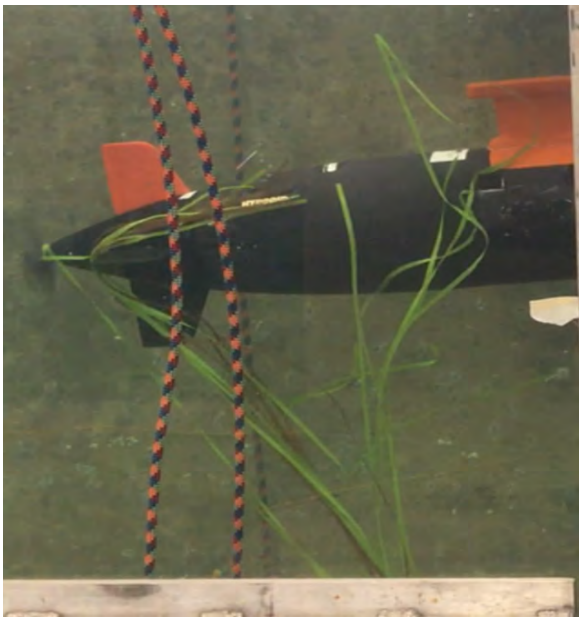


Figure 5.3. Entanglement Due to one Eelgrass Blade Wrapping around the Propeller Hub.

Major Finding 2: Entanglement Risk is Higher when Operating Astern

Figure 5.1 also shows that the entanglement risk is greater when operating astern propulsion. An evaluation of the REMUS body was done to determine the cause of this result. This analysis was conducted by reviewing video of vehicle travel through the marine vegetation field for forward and astern propulsion test conditions.

One possibility was that the bow generated a wake when approaching the vegetation field that pushed the field out of the way, resulting in a smaller likelihood of entanglement when operating forward propulsion. Figure 5.4 shows the vehicle approach to a single and low density eelgrass vegetation field when operating at [600 RPM, 0.17 m/s] , [900 RPM, 0.62 m/s], and [1200 RPM, 0.94 m/s] (forward propulsion). There is little to no forward deflection in the eelgrass vegetation field indicating that the bow wake generated by the REMUS has no significant effect on the entanglement risk. Additionally, an increase in vehicle steady state speed does not correlate to a larger bow wake or pushing force applied to the eelgrass field. Additionally, in several cases where an entanglement did not occur, eelgrass slid alongside the vehicle as opposed to the vehicle pushing it out of the way.

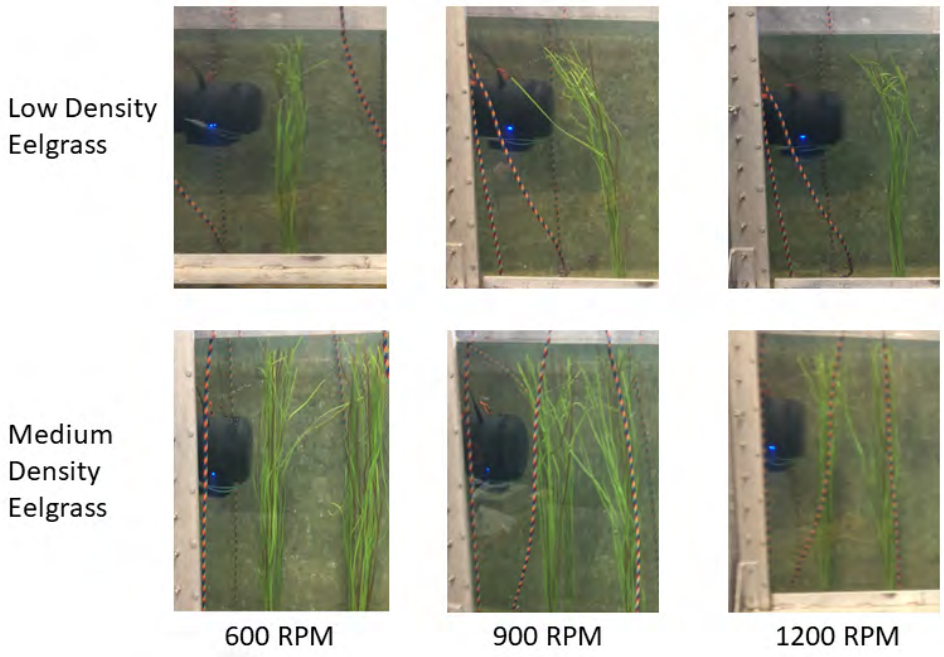
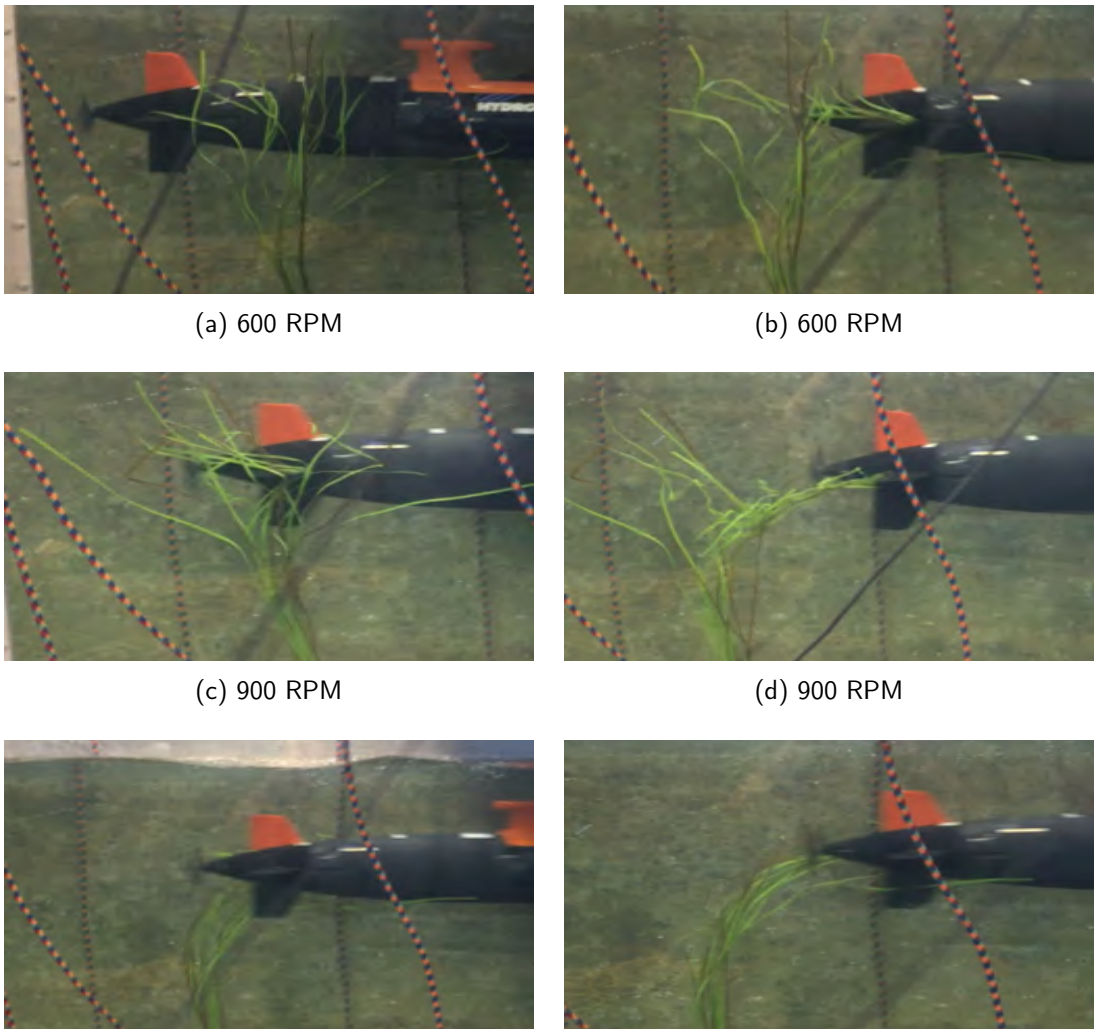


Figure 5.4. Evaluation of Bow Wake Generated by REMUS when Operating at 600, 900, and 1200 Forward RPM in Single and Low Density Eelgrass.

Control surface size and location of the vehicle may affect propeller entanglement risk. When operating with forward propulsion, the stern planes on the REMUS passed through the vegetation field prior to the propeller entrance; while operating with astern propulsion, the propeller was the first component of the vehicle to enter the field. Figure 5.5 shows the effect that the stern planes had on the eelgrass vegetation field for [600 RPM, 0.17 m/s] (figures a and b), [900 RPM, 0.62 m/s] (figures c and d), and [1200 RPM, 0.94 m/s] (figures e and f) (forward propulsion). Note that all of these test conditions resulted in no entanglement. As the stern planes entered the vegetation field, they pushed the eelgrass down and away from the propeller. The stern planes may minimize the risk of entanglement slightly; however, there were many cases in which entanglement occurred despite the stern planes interacting with the vegetation field, especially eelgrass.



(a) 600 RPM (b) 600 RPM

(c) 900 RPM (d) 900 RPM

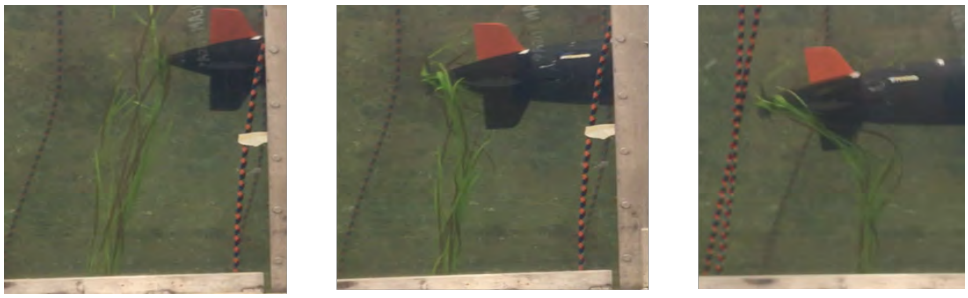
(e) 1200 RPM (f) 1200 RPM

Figure 5.5. Effect of Stern Planes on Eelgrass when Operating Forward Propulsion.

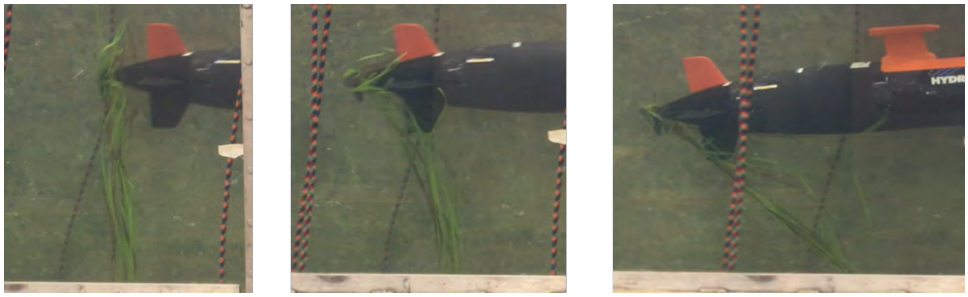
Figure 5.6 shows propeller entanglement in an eelgrass vegetation field for 600, 900, and 1200 RPM astern propulsion. All of these test conditions resulted in an entanglement kill. Figure (a) shows the propeller interactions that occur when operating at 600 RPM astern. At propeller entrance, eelgrass wrapping of the propeller hub occurs and continues until an entanglement kill occurs. The same sequence of events was observed for 900 and 1200 RPM astern propulsion as shown in figures (b) and (c). As the vehicle approaches the field,

there are no surfaces, such as the stern planes, to push the eelgrass away from the propeller. Therefore, propeller wrapping occurs immediately at vehicle/propeller entrance, ultimately resulting in an entanglement kill.

(a) 600 RPM



(b) 900 RPM



(c) 1200 RPM

Figure 5.6. Propeller Entanglement in Eelgrass when Operating Astern Propulsion.

Major Finding 3: Once Marine Vegetation Density Increases to a Critical Density Level, Entanglement Is Very Likely

Finally, results provided in Figure 5.1 show that the relationship between vegetation density and entanglement risk is not proportional; once a certain density level is reached, the entanglement risk significantly increases. Below this critical density level, entanglement is very unlikely, but still possible. For example, for forward propulsion in eelgrass, the risk of entanglement is minimal for single, low, and medium configurations; however, when the density is increased to a high configuration, the risk of entanglement for [600 RPM, 0.17 m/s] to [1000 RPM, 0.70 m/s] increases from minimal to very high.

As marine vegetation density increases, the number of entanglement opportunities increases. Additionally, a decrease in vehicle speed was visually observed for higher density vegetation configurations; this suggests that there may be a relationship between vehicle speed in the vegetation field and entanglement. As time in the marine vegetation field increases, the time available for propeller wrapping also increases.

5.3 Lateral Placement Entanglement Test

The lateral placement test was conducted to determine the impact that marine vegetation location relative to the center line of the vehicle and its propeller had on entanglement.

5.3.1 Lateral Placement Entanglement Test Results

Table 5.6 shows the lateral placement entanglement test results for the eelgrass configurations.

Table 5.6. Lateral Placement Entanglement Test Results for Eelgrass.

Distance from Vehicle Center line	Propulsion Direction	Trial 1	Trial 2	Trial 3
19.05 cm (7.5 in) port	Forward	N	N	N
11.43 cm (4.5 in) port	Forward	N	N	N
3.81 cm (1.5 in) port	Forward	N	N	N
3.81 cm (1.5 in) starboard	Forward	N	N	N
11.43 cm (4.5 in) starboard	Forward	N	N	N
19.05 cm (7.5 in) starboard	Forward	N	N	N
19.05 cm (7.5 in) port	Astern	N	N	N
11.43 cm (4.5 in) port	Astern	K	K	K
3.81 cm (1.5 in) port	Astern	K	K	K
center line	Astern	K	K	K
3.81 cm (1.5 in) starboard	Astern	K	K	K
11.43 cm (4.5 in) starboard	Astern	K	N	N
19.05 cm (7.5 in) starboard	Astern	K	N	N

Table 5.7 shows the lateral placement entanglement test results for giant kelp. No entanglement occurred When operating forward propulsion through a giant kelp field, indicating that no entanglement would occur during lateral placement testing when operating forward propulsion (annotated by "N*").

Table 5.7. Lateral Placement Entanglement Test Results for Giant Kelp.

Distance from Vehicle Center line	Propulsion Direction	Trial 1	Trial 2	Trial 3
20.48 cm (12 in) port	Forward	N*	N*	N*
15.24 cm (6 in) port	Forward	N*	N*	N*
15.24 cm (6 in) starboard	Forward	N*	N*	N*
20.48 cm (12 in) starboard	Forward	N*	N*	N*
20.48 cm (12 in) port	Astern	N	N	N
15.24 cm (6 in) port	Astern	N	N	N
15.24 cm (6 in) starboard	Astern	K	N	N
20.48 cm (12 in) starboard	Astern	N	K	N

5.3.2 Lateral Placement Entanglement Test Analysis

Figure 5.7 shows the number of entanglements, out of three trials, in eelgrass that occurred for the lateral placement test. Note that a negative distance from the propeller center line corresponds to a plant offset to port while a positive distance from the propeller center line corresponds to a plant offset to starboard. No entanglement occurred when operating forward propulsion. When operating astern propulsion, an eelgrass plant located -11.43, -3.81, 0, and 3.81 centimeters (-4.5, -1.5, 0, and 1.5 inches) from the propeller center line resulted in an entanglement kill for all three trials. An eelgrass plant located 11.43 and 19.05 centimeters (4.5 and 7.5 inches) from the propeller center line resulted in an entanglement kill for one out of three trials. All other configurations resulted in zero entanglement kills.

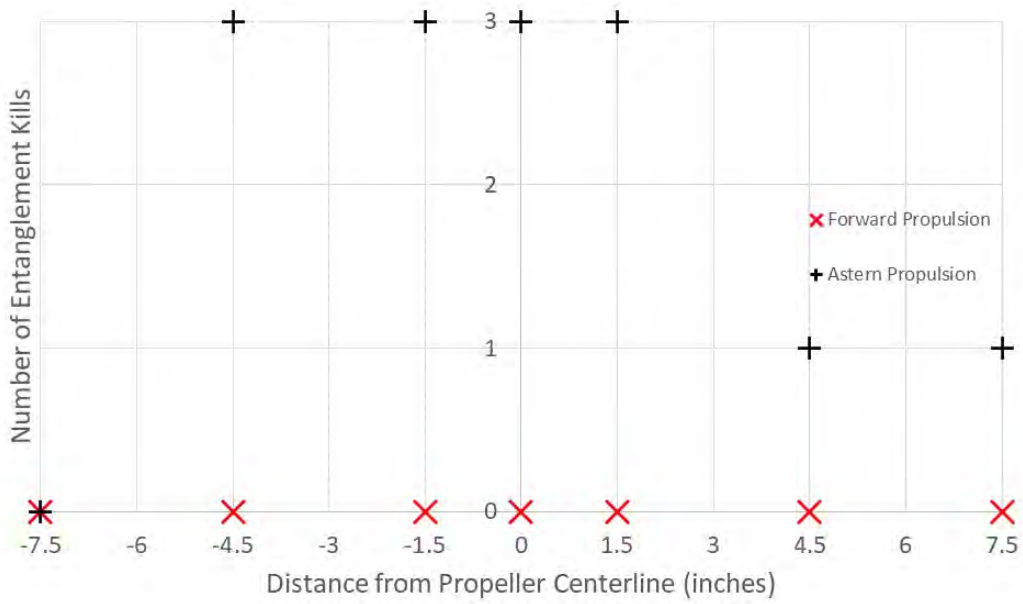


Figure 5.7. Entanglement Results for the Eelgrass Lateral Placement Entanglement Test.

Figure 5.8 shows the number of entanglements, out of three trials, in giant kelp that occurred for the lateral placement test. A negative distance from the propeller center line corresponds to a plant offset to port while a positive distance from the propeller center line corresponds to a plant offset to starboard. No entanglement occurred when operating forward propulsion. When operating astern propulsion a giant kelp plant located 0 centimeters (0 inches) from the propeller center line resulted in an entanglement kill for all three trials. A giant kelp plant located 15.24 and 30.48 centimeters (6 and 12 inches) from the propeller center line resulted in an entanglement kill for one out of three trials. All other configurations resulted in zero entanglement kills.

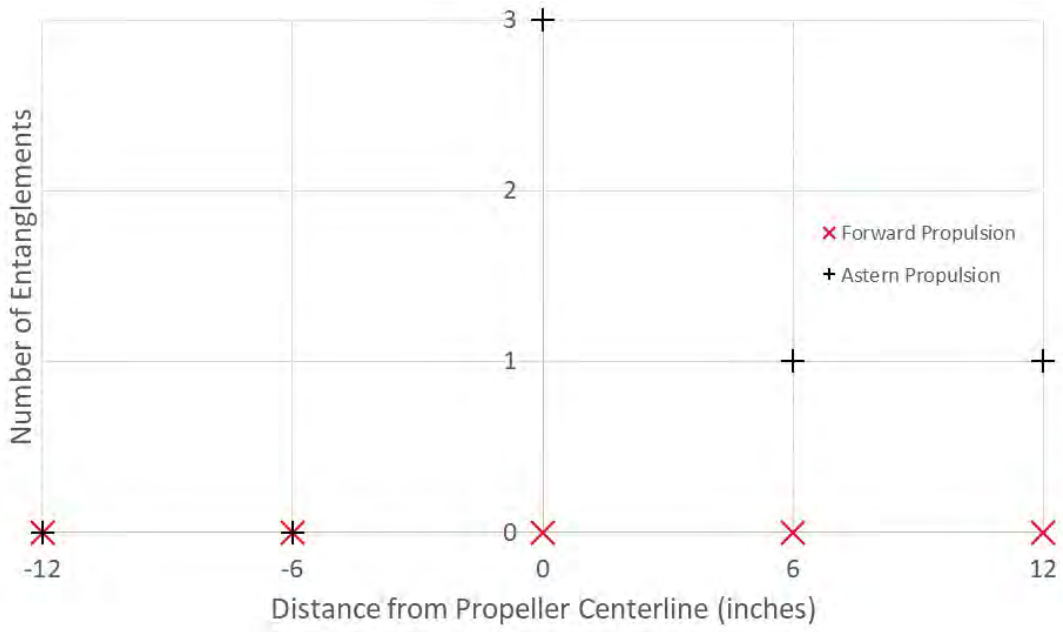


Figure 5.8. Entanglement Results for the Giant Kelp Lateral Placement Entanglement Test.

Major Finding 4: As the Distance between the Marine Vegetation and Vehicle Propeller Decreases, the Number of Entanglements Increases

As shown above, a decrease in distance between the propeller and marine vegetation location generally resulted in an increase in entanglements. As plant distance from the propeller increased, the level of interaction between the propeller (entanglement surface) decreased.

Figure 5.9 shows the interaction between the propeller and eelgrass when operating forward propulsion. While no entanglement occurred for forward propulsion conditions, propeller interaction with eelgrass blades increased as plant distance from the propeller center line decreased. As the propeller entered the eelgrass plant placed 19.05 centimeters (7.5 inches) away, minimal interaction and no propeller blade or hub wrapping occurred. As the distance was decreased to 11.43 and 3.81 centimeters (4.5 and 1.5 inches), the propeller began to pull eelgrass blades towards it, increasing the risk for propeller blade and hub wrapping. Finally, when travelling through a plant located center line, initial propeller wrapping began to occur but was not sufficient to cause an entanglement event or kill.

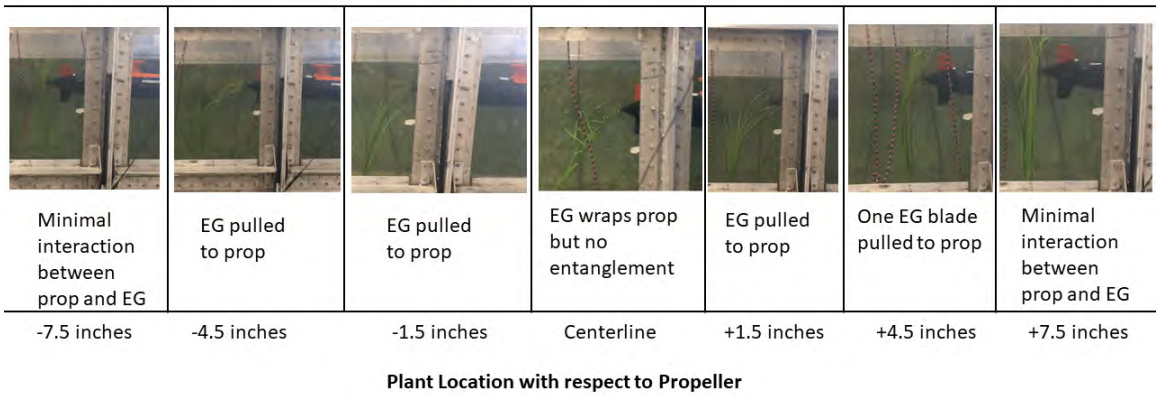


Figure 5.9. Propeller and Vegetation Interactions Observed in the Lateral Placement Entanglement Test when Operating Forward Propulsion in Eelgrass.

Figure 5.10 shows the interaction between the propeller and eelgrass when operating astern propulsion for each lateral placement configuration. Each lateral placement configuration, except the -7.5 inch case, shows two stages of one test run: the onset of propeller wrapping and the continued propeller wrapping that resulting in an entanglement kill. All except the -19.05 centimeters (-7.5 inches) placement condition show that contact between the propeller and eelgrass occurred during propeller entrance. Propeller hub wrapping followed this initial contact. Continued propeller hub and blade wrapping resulted in entanglement. The severity of the entanglement resulting from a center line plant configuration was the worst indicated by how tightly wrapped the propeller was by eelgrass at the time of entanglement.

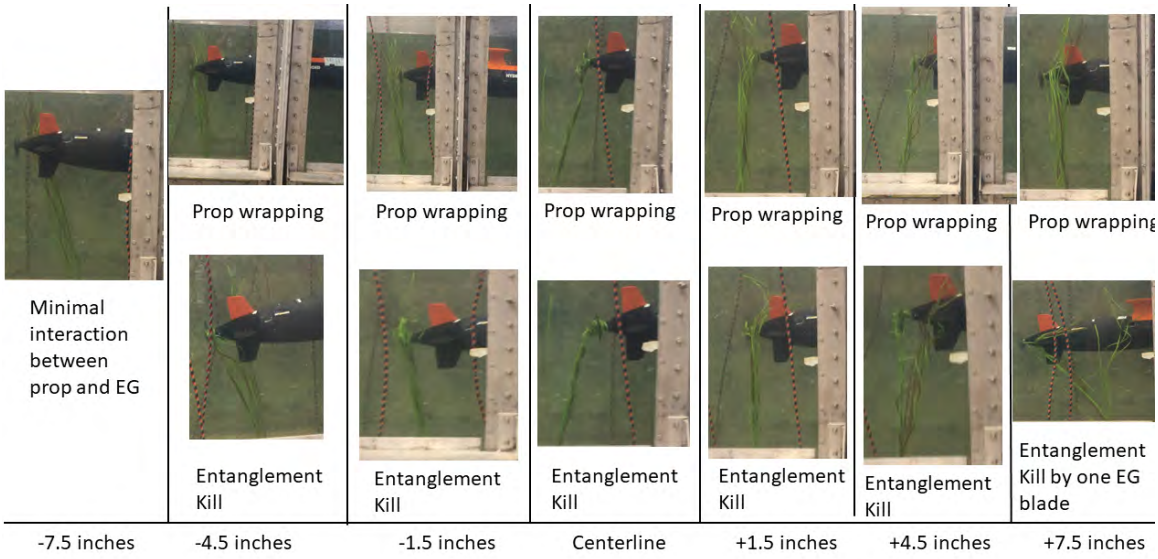


Figure 5.10. Propeller and Vegetation Interactions Observed in the Lateral Placement Entanglement Test when Operating Astern Propulsion in Eelgrass.

Figure 5.11 shows the interaction between the propeller and giant kelp when operating astern propulsion for each lateral placement configuration. Two instances in time for a run conducted for each lateral placement configuration is provided to show different interactions between the giant kelp and propeller (pulling effects, propeller wrapping, entanglement). As the distance between the propeller and giant kelp plant decreased, a pulling effect on the plant by the propeller was observed visually. In most cases, this pulling effect enabled initial propeller hub wrapping.

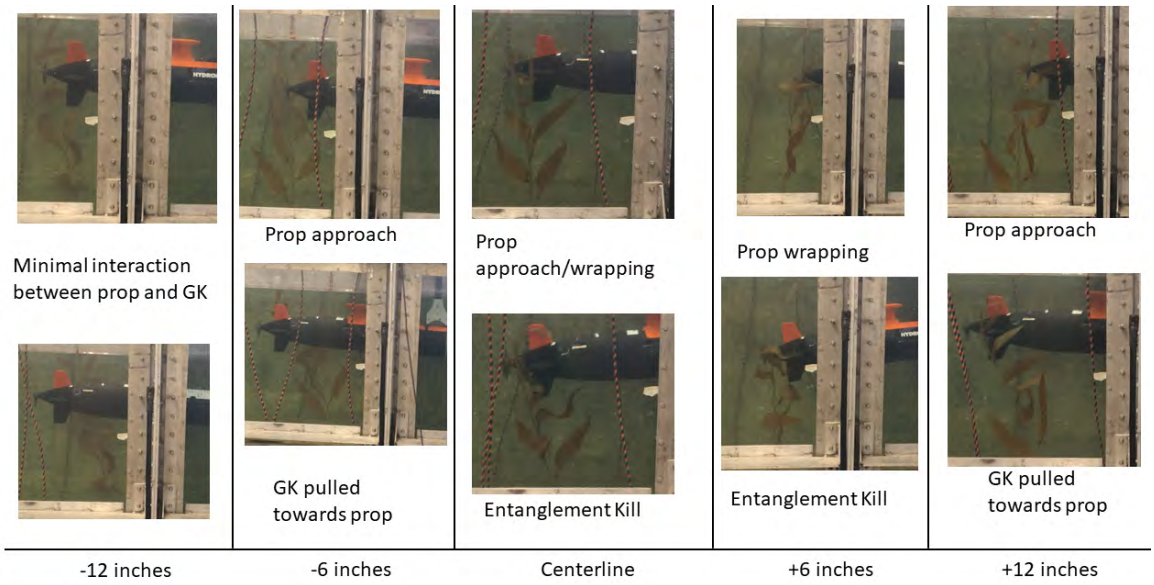


Figure 5.11. Propeller and Vegetation Interactions Observed in the Lateral Placement Entanglement Test when Operating Astern Propulsion in Giant Kelp.

Major Finding 5: Propeller Diameter of the Vehicle Impacts Entanglement

Figures 5.9, 5.10, and 5.11 and entanglement results for the eelgrass lateral placement entanglement test indicate that there is a correlation between propeller size, distance from vegetation, and risk of entanglement. In forward lateral tests, there was an observed interaction between the propeller and eelgrass when the vegetation field was within one propeller spacing away (11.43 centimeters/4.5 inches). In astern lateral tests, there was a higher risk of entanglement when the vegetation field was within one propeller spacing away.

Figure 5.12 shows the REMUS propeller. Entanglement is a result of propeller wrapping; therefore, the area encased by the propeller blades is related to vulnerable entanglement area for the vehicle.

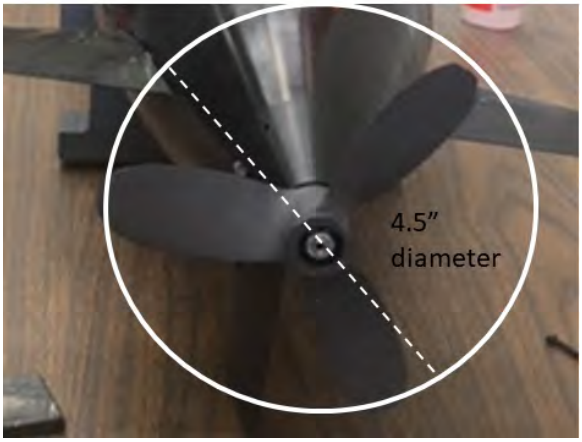


Figure 5.12. Propeller Diameter.

5.4 Accelerating Speed Entanglement Test

In the vegetation density and constant speed test, the propeller RPM and vehicle speed were correlated. The accelerating speed test was conducted to decouple propeller RPM from vehicle speed to determine if propeller RPM or vehicle speed, individually, were important with respect to entanglement.

5.4.1 Accelerating Speed Entanglement Test Results

Table 5.4.1 shows the results of the accelerating speed entanglement test. This was a preliminary test and an equal number of trials were not run for all conditions (annotated as "NA").

Table 5.8. Accelerating Speed Entanglement Test Results.

RPM	Propeller Distance from Vegetation Field	Trial 1	Trial 2	Trial 3
600	1.525 m (5 ft)	E	N	NA
600	1.22 m (4 ft)	E	NA	NA
600	0.915 m (3 ft)	K	NA	NA

Continued on next page

Table 5.8 – *Continued from previous page*

RPM	Propeller Distance from Vegetation Field	Trial 1	Trial 2	Trial 3
600	0.61 m (2 ft)	NA	NA	NA
600	0.305 m (1 ft)	NA	NA	NA
700	1.525 m (5 ft)	N	NA	NA
700	1.22 m (4 ft)	N	K	E
700	0.915 m (3 ft)	N	E	N
700	0.61 m (2 ft)	N	N	N
700	0.305 m (1 ft)	K	E	E
800	1.525 m (5 ft)	N	NA	NA
800	1.22 m (4 ft)	E	N	N
800	0.915 m (3 ft)	E	E	N
800	0.61 m (2 ft)	E	E	E
800	0.305 m (1 ft)	K	K	K
900	1.525 m (5 ft)	N	NA	NA
900	1.22 m (4 ft)	E	E	N
900	0.915 m (3 ft)	E	K	E
900	0.61 m (2 ft)	K	K	K
900	0.305 m (1 ft)	NA	NA	NA
1000	1.525 m (5 ft)	N	E	N
1000	1.22 m (4 ft)	N	E	E
1000	0.915 m (3 ft)	E	K	E
1000	0.61 m (2 ft)	K	E	E
1000	0.305 m (1 ft)	E	K	K
1100	1.525 m (5 ft)	N	NA	NA
1100	1.22 m (4 ft)	N	N	E
1100	0.915 m (3 ft)	K	K	K
1100	0.61 m (2 ft)	NA	NA	NA
1100	0.305 m (1 ft)	NA	NA	NA
1200	1.525 m (5 ft)	N	N	NA

Continued on next page

Table 5.8 – *Continued from previous page*

RPM	Propeller Distance from Vegetation Field	Trial 1	Trial 2	Trial 3
1200	1.22 m (4 ft)	N	NA	NA
1200	0.915 m (3 ft)	N	NA	NA
1200	0.61 m (2 ft)	K	K	K
1200	0.305 m (1 ft)	NA	NA	NA

5.4.2 Accelerating Speed Entanglement Test Analysis

A preliminary analysis of propeller entrance speed and entanglement was conducted using speed calibration data and results. For each RPM tested (600 to 1200 in 100 RPM increments), the distance between the propeller and vegetation field entrance was changed to determine if propeller entrance speed had an impact on entanglement. Propeller entrance speed for the different vehicle starting positions and propeller RPMs was determined using the graph for speed as a function of position generated in the speed calibration. These propeller entrance speeds are provided in Table 5.9.

Table 5.9. Propeller Entrance Speed as a Function of RPM and Distance from Vegetation Field.

Propeller RPM	Distance from Vegetation Field	Entrance Speed
600	1.525 m (5 ft)	0.1414 m/s (0.464 ft/s)
	1.22 m (4 ft)	0.1414 m/s (0.464 ft/s)
	0.915 m (3 ft)	0.1338 m/s (0.439 ft/s)
	0.61 m (2 ft)	0.1113 m/s (0.0.3652 ft/s)
	0.305 m (1 ft)	0.0835 m/s (0.274 ft/s)
700	1.525 m (5 ft)	0.1966 m/s (0.6451 ft/s)
	1.22 m (4 ft)	0.1966 m/s (0.6451 ft/s)

Continued on next page

Table 5.9 – *Continued from previous page*

Propeller RPM	Distance from Vegetation Field	Entrance Speed
700	0.915 m (3 ft)	0.1966 m/s (0.6449 ft/s)
	0.61 m (2 ft)	0.1960 m/s (0.6431 ft/s)
	0.305 m (1 ft)	0.1882 m/s (0.6174 ft/s)
800	1.525 m (5 ft)	0.4005 m/s (1.314 ft/s)
	1.22 m (4 ft)	0.37338 m/s (1.225 ft/s)
	0.915 m (3 ft)	0.3383 m/s (1.11 ft/s)
	0.61 m (2 ft)	0.2869 m/s (0.9412 ft/s)
	0.305 m (1 ft)	0.2044 m/s (0.6707 ft/s)
900	1.525 m (5 ft)	0.44897 m/s (1.473 ft/s)
	1.22 m (4 ft)	0.4164 m/s (1.366 ft/s)
	0.915 m (3 ft)	0.3752 m/s (1.231 ft/s)
	0.61 m (2 ft)	0.3234 m/s (1.061 ft/s)
	0.305 m (1 ft)	0.2501 m/s (0.8206 ft/s)
1000	1.525 m (5 ft)	0.5669 m/s (1.86 ft/s)
	1.22 m (4 ft)	0.5544 m/s (1.819 ft/s)
	0.915 m (3 ft)	0.5294 m/s (1.737 ft/s)
	0.61 m (2 ft)	0.4813 m/s (1.579 ft/s)
	0.305 m (1 ft)	0.3719 m/s (1.22 ft/s)
1100	1.525 m (5 ft)	0.7004 m/s (2.298 ft/s)
	1.22 m (4 ft)	0.6538 m/s (2.145 ft/s)
	0.915 m (3 ft)	0.5879 m/s (1.926 ft/s)
	0.61 m(2 ft)	0.4938 m/s (1.62 ft/s)
	0.305 m (1 ft)	0.2579 m/s (0.8461 ft/s)
1200	1.525 m (5 ft)	0.77297 m/s (2.536 ft/s)
	1.22 m (4 ft)	0.7178 m/s (2.355 ft/s)
	0.915 m (3 ft)	0.6483 m/s (2.127 ft/s)
	0.61 m (2 ft)	0.5453 m/s (1.789 ft/s)
	0.305 m (1 ft)	0.3749 m/s (1.23 ft/s)

Figure 5.13 shows the number of no entanglements, entanglement events, and entanglement kills as a function of propeller entrance speed. No entanglement conditions are marked with a green plus sign, entanglement events are marked with a yellow triangle, and entanglement kills are marked with a red x.

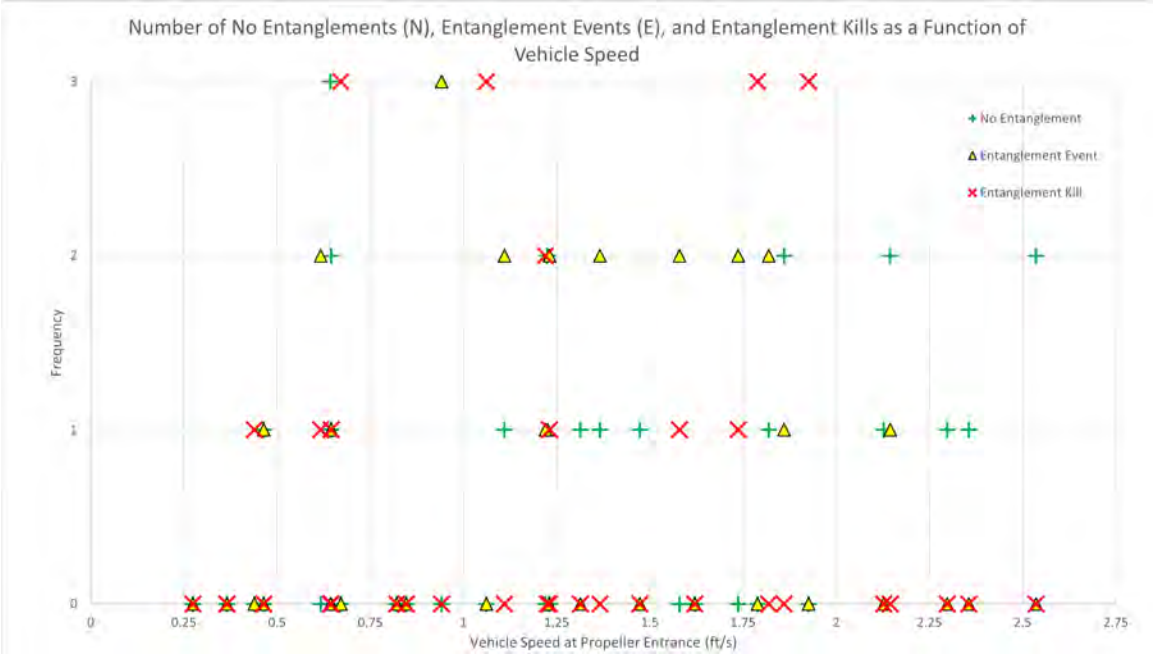


Figure 5.13. Frequency of No Entanglements, Entanglement Events, and Entanglement Kills as a Function of Vehicle Speed at Propeller Entrance.

Major Finding 6: As the Ratio of Propeller Entrance Speed to Steady State Speed Decreases, the Likelihood of Entanglement Increases

Entrance speed and the frequency of entanglement conditions were used to analyze the effect of speed ratio on the likelihood of entanglement. Equation 5.1 was used to calculate the speed ratio. Table 5.4.2 shows the speed ratios for each test condition.

$$\text{Speed ratio} = \frac{\text{Entrance Speed}}{\text{Steady State Speed}} \tag{5.1}$$

Table 5.10. Calculated Speed Ratio for each Accelerating Speed Test Run.

RPM	Propeller Distance from Vegetation Field	Speed Ratio
600	1.525 m (5 ft)	0.82
600	1.22 m (4 ft)	0.82
600	0.915 m (3 ft)	0.78
600	0.61 m (2 ft)	0.65
600	0.305 m (1 ft)	0.48
700	1.525 m (5 ft)	1.00
700	1.22 m (4 ft)	1.00
700	0.915 m (3 ft)	1.00
700	0.61 m (2 ft)	1.00
700	0.305 m (1 ft)	0.96
800	1.525 m (5 ft)	0.85
800	1.22 m (4 ft)	0.79
800	0.915 m (3 ft)	0.72
800	0.61 m (2 ft)	0.61
800	0.305 m (1 ft)	0.43
900	1.525 m (5 ft)	0.73
900	1.22 m (4 ft)	0.67
900	0.915 m (3 ft)	0.61
900	0.61 m (2 ft)	0.52
900	0.305 m (1 ft)	0.40
1000	1.525 m (5 ft)	0.81
1000	1.22 m (4 ft)	0.80
1000	0.915 m (3 ft)	0.76
1000	0.61 m (2 ft)	0.69
1000	0.305 m (1 ft)	0.53
1100	1.525 m (5 ft)	0.85
1100	1.22 m (4 ft)	0.79

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Table 5.10 – *Continued from previous page*

RPM	Propeller Distance from Vegetation Field	Speed Ratio
1100	0.915 m (3 ft)	0.71
1100	0.61 m (2 ft)	0.60
1100	0.305 m (1 ft)	0.31
1200	1.525 m (5 ft)	0.82
1200	1.22 m (4 ft)	0.77
1200	0.915 m (3 ft)	0.69
1200	0.61 m (2 ft)	0.58
1200	0.305 m (1 ft)	0.40

Figure 5.14 shows the probability of no entanglement (green plus sign), entanglement event (yellow triangle), and entanglement kill (red x) for the speed ratios tested. As the speed ratio increases, the probability of an entanglement kill decreases and the probability of no entanglement increases. Linear trend lines for the probability of no entanglement (green dashed line) and for the probability of an entanglement kill (red dashed line) are provided to represent this general relationship between the speed ratio and the probability of entanglement. Entanglement events bridge the gap between no entanglement and entanglement kill conditions based on entanglement being a stochastic event; overall, any entanglement condition (event or kill) decreases as the speed ratio increases. For speed ratio less 0.6, an entanglement kill is very likely. For a speed ratio between 0.6 and 0.8, an entanglement event is very likely, with an entanglement kill resulting in half of the cases. For a speed ratio greater than 0.8, an entanglement event occurs in half of the case and, while an entanglement kill is possible, it occurs infrequently.

Figure 5.14. Probability of No Entanglement, Entanglement Event, and Entanglement Kill as a Function of Speed Ratio.

As the speed ratio increases, the time the propeller remains in the vegetation field decreases. This decreases the interaction time between the propeller and the vegetation, decreasing the time frame during which initial propeller wrapping and follow-on wrapping can occur. Time in the vegetation field and the propeller RPM also affect the number of blade rotations that occur when the vehicle is in the vegetation field.

During testing, it was also observed that high density vegetation concentrations caused the vehicle to slow as it entered the vegetation field. This visual observation and the speed ratio results suggest that dense kelp fields could slow the vehicle down enough that entanglement occurs; however, future work is required to test this hypothesis.

Major Finding 7: The Line between Entanglement and No Entanglement is Dynamic and Unstable

While there is a trend between speed ratio and probability of entanglement, there is no clear line between an entanglement and no entanglement condition. Propeller wrapping was observed in all entanglement events and entanglement kills, but was also observed in some no entanglement conditions. While there is a relationship between speed ratio and the

likelihood of entanglement, there is no speed ratio that characterizes a definitive line between entanglement and no entanglement. For example, the speed ratios associated with 700 RPM runs corresponding with propeller distances of 1.525, 1.22, 0.915, 0.61, and 0.305 meters (5, 4, 3, 2, and 1 feet) were 1, 1, 1, 1, and 0.96, respectively. Entanglement and no entanglement conditions were observed for speed ratios of 1 and entanglements were observed for the speed ratio of 0.96. For most runs associated with this RPM, an initial wrapping of eelgrass on the vehicle propeller occurred; however, not all of these propeller wrapping cases caused a disruption of vehicle motion through the field resulting in an entanglement event or kill. A slight modification to initial conditions such as entrance speed, speed ratio, vegetation placement, and density may be sufficient to change the entanglement outcome of these scenarios.

5.5 Chapter Summary

This chapter discussed the major findings of the three entanglement tests conducted in this thesis. As shown by results from the vegetation density and constant speed entanglement test, eelgrass entanglement risk is greater than giant kelp entanglement risk, entanglement risk is higher when operating astern propulsion, and as the marine vegetation density increases to a critical density level, entanglement is very likely. Lateral placement entanglement tests indicate that the number of entanglements increases as the distance between a marine vegetation field and the vehicle propeller decreases and that the size of the vehicle propeller has an impact on entanglement. Finally, the accelerating speed entanglement test suggests that as the vehicle speed ratio increases, the likelihood of entanglement decreases and that the line between entanglement and no entanglement is dynamic and unstable. The next section will discuss recommendations for future work.

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CHAPTER 6:
Recommendations for Future Work

6.1 Chapter Introduction

This chapter provides recommendations for future work. More extensive accelerating speed entanglement testing would provide greater fidelity to results and would provide more data to support the hypothesis that vehicle speed and propeller RPM through the vegetation field has a significant impact on entanglement. Testing in an open ocean environment would provide entanglement data for typical areas of operation. Entanglement solutions that can be applied to the DOD's current inventory of REMUS 100 vehicles should be explored. Finally, entanglement of UUVs that use propulsive mechanisms other than an open three-bladed propeller should be evaluated.

6.2 Expand on Accelerating Speed Entanglement Testing

The accelerating speed entanglement testing was conducted as a preliminary evaluation of the effect of instantaneous vehicle speed on the probability of entanglement. The number of trials conducted for each configuration was not consistent and only one vegetation configuration was evaluated. The author recommends follow-on testing of the relationship between the vehicle speed at propeller entrance and the probability of entanglement for low, medium, and high density marine vegetation environments. Visually, it was observed that higher density vegetation configurations caused the vehicle to slow down as it entered; therefore, it is recommended that vehicle speed is measured throughout each test run to determine if speed through the vegetation field or vegetation density has more of an impact on propeller entanglement.

6.3 Real-World Testing Environment

The testing environment provided limitations on vehicle speed and actual operating environment. RPMs above 1200 were not tested due to length of the tank and stopping distance required and RPMs below 600 were not tested due to the propeller thrust required to over-

come the frictional force imposed by the text fixture. Testing in an open ocean environment would eliminate these limitations and allow complete testing of the vehicle's propulsion system. Testing in the real world environment would also provide entanglement data for real marine vegetation as opposed to synthetic vegetation. As discussed previously, the single representative piece of real giant kelp had a higher deflection and more blades than the synthetic giant kelp used in this work. This higher deflection may make it more likely that a real giant kelp stipe will wrap and entangle the propeller. Vehicle travel may also be impacted/disrupted by the higher density blade observed for the single representative piece of real giant kelp, resulting in more instances of entanglement. Finally, testing in a typical area of operation would provide data on other types of entanglement concerns such as silt and other marine vegetation types.

6.4 Entanglement Solutions

Future work on entanglement solutions for UUVs is required, especially as they become more operationally relevant. Possible solutions include entanglement protection devices, such as those discussed in Chapter 1, and operational procedures. As seen in this work, entanglement was caused by marine vegetation wrapping around the propeller blades and propeller hub; a propeller guard that prevented this wrapping may be an entanglement solution. When disentangling the propeller between test runs, there were some cases in which the disentanglement effort was helped by jockeying the propeller RPM forward and astern; while this did not help in all entanglement cases, it may help disentangle the vehicle in less severe entanglement cases.

6.5 Alternative UUV Types and Entanglement

It is recommended future work evaluates entanglement of UUVs propelled by different types of propulsive mechanisms. This work evaluates the entanglement of an open three-bladed propeller while other UUVs are propelled by biomimetic means, tunnel thrusters, and other means. Possible UUV types recommended for future testing include the GhostSwimmer and BlueROV2 discussed in Chapter 1.

6.6 Chapter Summary

This chapter discussed recommendations for future work on UUV entanglement in marine vegetation. Further testing is required to evaluate the effect of accelerating speed through a vegetation field on entanglement. Testing in a real world environment would allow the full range of the propulsion system to be tested, evaluate the entanglement risk in real marine vegetation, and help to identify other entanglement concerns. The author also recommends further research on entanglement solutions that would decrease the risk of entanglement when operating and/or help with disentanglement measures to prevent the loss of the vehicle. Finally, entanglement testing of other UUVs that use different propulsive mechanisms, such as the GhostSwimmer and BlueROV2, is recommended.

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APPENDIX A:
REMUS Speed Calibration Data

The following tables provide the data collected during the speed calibration tests. There are twelve total tables in this appendix, one for each of the twelve speeds that we tested during the calibration portion of the testing. The amount of data collected requires that the tables be broken across multiple pages.

The first column of data corresponds to the time, in seconds, that the data point was collected. The second column is the voltage reading from the Senix Ultrasonic sensor that is proportional to the displacement of the carriage from the sensor. The voltage can be converted into a physical displacement, or position, of the carriage by using the gain factor of 30 inches/volt.

The following pages contain the tables.

Table A.1. Position Sensor Data for 600 RPM.

Time	Voltage
0.000000	9.945982
0.041667	9.932135
0.083333	9.930525
0.125000	9.934067
0.166667	9.938897
0.208333	9.939541
0.250000	9.936321
0.291667	9.930525
0.333333	9.934389
0.375000	9.938575
0.416667	9.939541
0.458333	9.947914
0.500000	9.935033
0.541667	9.932457
0.583333	9.940185
0.625000	9.940829
0.666667	9.946304
0.708333	9.950490
0.750000	9.937931
0.791667	9.935999
0.833333	9.941473

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Time	Voltage
0.875000	9.941795
0.916667	9.944694
0.958333	9.949846
1.000000	9.936965
1.041667	9.937287
1.083333	9.936965
1.125000	9.934067
1.166666	9.943728
1.208333	9.943406
1.250000	9.931813
1.291666	9.932135
1.333333	9.935677
1.375000	9.936965
1.416666	9.941795
1.458333	9.948236
1.500000	9.935999
1.541666	9.935999
1.583333	9.935033
1.625000	9.939219
1.666666	9.945016
1.708333	9.945660
1.750000	9.933745
1.791666	9.929559

Continued on next column

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Time	Voltage
1.833333	9.934067
1.875000	9.936965
1.916666	9.941795
1.958333	9.945338
2.000000	9.933745
2.041666	9.929881
2.083333	9.935033
2.125000	9.940829
2.166666	9.939863
2.208333	9.944050
2.250000	9.930847
2.291666	9.926983
2.333333	9.934389
2.375000	9.934389
2.416666	9.937609
2.458333	9.940507
2.500000	9.928915
2.541666	9.931169
2.583333	9.928915
2.625000	9.931169
2.666666	9.930203
2.708333	9.935677
2.750000	9.924406

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Time	Voltage
2.791666	9.923118
2.833333	9.923118
2.875000	9.925372
2.916666	9.927627
2.958333	9.928915
3.000000	9.916678
3.041666	9.912492
3.083333	9.912814
3.124999	9.917322
3.166666	9.916034
3.208333	9.917000
3.249999	9.903475
3.291666	9.904763
3.333333	9.905085
3.374999	9.905729
3.416666	9.905407
3.458333	9.904763
3.499999	9.891882
3.541666	9.889628
3.583333	9.890916
3.624999	9.890594
3.666666	9.893492
3.708333	9.893170

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Time	Voltage
3.749999	9.883188
3.791666	9.879646
3.833333	9.878036
3.874999	9.875781
3.916666	9.876103
3.958333	9.879324
3.999999	9.866121
4.041666	9.863867
4.083333	9.864189
4.124999	9.861935
4.166666	9.862257
4.208333	9.863223
4.249999	9.849698
4.291666	9.850986
4.333333	9.849376
4.374999	9.847444
4.416666	9.847122
4.458333	9.846478
4.499999	9.833597
4.541666	9.830055
4.583333	9.833597
4.624999	9.832309
4.666666	9.833919

Continued on next column

Continued from previous column

Time	Voltage
4.708333	9.831987
4.749999	9.819106
4.791666	9.818140
4.833333	9.818140
4.874999	9.816208
4.916666	9.813954
4.958333	9.818140
4.999999	9.804615
5.041666	9.801395
5.083333	9.799141
5.124999	9.798497
5.166666	9.796564
5.208333	9.800107
5.249999	9.787226
5.291666	9.783684
5.333332	9.783684
5.374999	9.779819
5.416666	9.779497
5.458332	9.783362
5.499999	9.769515
5.541666	9.765329
5.583332	9.765007
5.624999	9.762430

Continued on next column

Continued from previous column

Time	Voltage
5.666666	9.759854
5.708332	9.761786
5.749999	9.748906
5.791666	9.748584
5.833332	9.741821
5.874999	9.742465
5.916666	9.740855
5.958332	9.738601
5.999999	9.726364
6.041666	9.726042
6.083332	9.726042
6.124999	9.720890
6.166666	9.721534
6.208332	9.720568
6.249999	9.708975
6.291666	9.704789
6.333332	9.705755
6.374999	9.701569
6.416666	9.704467
6.458332	9.699314
6.499999	9.686756
6.541666	9.684502
6.583332	9.684502

Continued on next column

Continued from previous column

Time	Voltage
6.624999	9.681281
6.666666	9.683214
6.708332	9.681281
6.749999	9.669045
6.791666	9.663248
6.833332	9.661638
6.874999	9.660028
6.916666	9.661316
6.958332	9.661960
6.999999	9.649079
7.041666	9.648435
7.083332	9.643283
7.124999	9.640707
7.166666	9.639097
7.208332	9.638131
7.249999	9.625572
7.291665	9.627504
7.333332	9.621386
7.374999	9.622030
7.416665	9.616877
7.458332	9.618810
7.499999	9.605285
7.541665	9.603031

Continued on next column

Continued from previous column

Time	Voltage
7.583332	9.594658
7.624999	9.595302
7.666665	9.592726
7.708332	9.587574
7.749999	9.571473
7.791665	9.575659
7.833332	9.570507
7.874999	9.571473
7.916665	9.566642
7.958332	9.564388
7.999999	9.552152
8.041665	9.550863
8.083332	9.549575
8.124999	9.543779
8.166665	9.539915
8.208332	9.541847
8.249999	9.528322
8.291665	9.524458
8.333332	9.519628
8.374999	9.516729
8.416665	9.514797
8.458332	9.514153
8.499999	9.499984

Continued on next column

Continued from previous column

Time	Voltage
8.541665	9.496442
8.583332	9.494832
8.624999	9.490324
8.666665	9.491612
8.708332	9.484205
8.749999	9.471325
8.791665	9.468748
8.833332	9.464884
8.874999	9.460698
8.916665	9.456190
8.958332	9.455546
8.999999	9.444275
9.041665	9.436869
9.083332	9.436547
9.124999	9.430428
9.166665	9.425598
9.208332	9.424954
9.249999	9.411107
9.291665	9.403701
9.333332	9.400802
9.374999	9.395972
9.416665	9.394684
9.458332	9.394684

Continued on next column

Continued from previous column

Time	Voltage
9.499998	9.381159
9.541665	9.371821
9.583332	9.368601
9.624998	9.364092
9.666665	9.361194
9.708332	9.354432
9.749998	9.340585
9.791665	9.338331
9.833332	9.330280
9.874998	9.327704
9.916665	9.321264
9.958332	9.319332
9.999998	9.304841
10.041665	9.298400
10.083332	9.291316
10.124998	9.288740
10.166665	9.284876
10.208332	9.281011
10.249998	9.269741
10.291665	9.259758
10.333332	9.252352
10.374998	9.250097
10.416665	9.241725

Continued on next column

Continued from previous column

Time	Voltage
10.458332	9.240115
10.499998	9.226590
10.541665	9.218218
10.583332	9.209523
10.624998	9.207591
10.666665	9.200507
10.708332	9.196964
10.749998	9.185372
10.791665	9.170237
10.833332	9.165084
10.874998	9.162508
10.916665	9.155102
10.958332	9.148339
10.999998	9.133527
11.041665	9.126764
11.083332	9.121290
11.124998	9.114527
11.166665	9.105189
11.208332	9.102613
11.249998	9.090054
11.291665	9.073309
11.333332	9.070089
11.374998	9.063327

Continued on next column

Continued from previous column

Time	Voltage
11.416665	9.057852
11.458331	9.052700
11.499998	9.036921
11.541665	9.029515
11.583331	9.022430
11.624998	9.015346
11.666665	9.010515
11.708331	9.008905
11.749998	8.990550
11.791665	8.982500
11.833331	8.975737
11.874998	8.969297
11.916665	8.962213
11.958331	8.961247
11.999998	8.941603
12.041665	8.934841
12.083331	8.926791
12.124998	8.919706
12.166665	8.915520
12.208331	8.909402
12.249998	8.896199
12.291665	8.888148
12.333331	8.881708

Continued on next column

Continued from previous column

Time	Voltage
12.374998	8.876556
12.416665	8.873980
12.458331	8.868183
12.499998	8.851116
12.541665	8.844032
12.583331	8.837591
12.624998	8.832117
12.666665	8.828897
12.708331	8.821813
12.749998	8.808610
12.791665	8.800559
12.833331	8.795729
12.874998	8.789289
12.916665	8.782204
12.958331	8.777696
12.999998	8.766425
13.041665	8.759985
13.083331	8.752257
13.124998	8.747104
13.166665	8.740664
13.208331	8.738410
13.249998	8.721343
13.291665	8.715547

Continued on next column

Continued from previous column

Time	Voltage
13.333331	8.708140
13.374998	8.705564
13.416665	8.697191
13.458331	8.694937
13.499998	8.680447
13.541664	8.674650
13.583331	8.666600
13.624998	8.662091
13.666664	8.655973
13.708331	8.652109
13.749998	8.635042
13.791664	8.632788
13.833331	8.626347
13.874998	8.621195
13.916664	8.615077
13.958331	8.613789
13.999998	8.600586
14.041664	8.595112
14.083331	8.586095
14.124998	8.582231
14.166664	8.579011
14.208331	8.577079
14.249998	8.560012

Continued on next column

Continued from previous column

Time	Voltage
14.291664	8.555181
14.333331	8.550673
14.374998	8.543267
14.416664	8.540369
14.458331	8.538115
14.499998	8.520082
14.541664	8.516217
14.583331	8.510099
14.624998	8.504303
14.666664	8.500116
14.708331	8.499472
14.749998	8.482727
14.791664	8.480473
14.833331	8.471779
14.874998	8.469525
14.916664	8.461796
14.958331	8.461152
14.999998	8.443441

Table A.2. Position Sensor Data for 700 RPM.

Time	Voltage
0.000000	9.658740
0.041667	9.661960
0.083333	9.642961
0.125000	9.637165
0.166667	9.634589
0.208333	9.629758
0.250000	9.626538
0.291667	9.630402
0.333333	9.608183
0.375000	9.606251
0.416667	9.596590
0.458333	9.595946
0.500000	9.592082
0.541667	9.595946
0.583333	9.572761
0.625000	9.567286
0.666667	9.561812
0.708333	9.557304
0.750000	9.554084
0.791667	9.556982
0.833333	9.539593

Continued on next column

Continued from previous column

Time	Voltage
0.875000	9.529288
0.916667	9.524458
0.958333	9.521560
1.000000	9.513831
1.041667	9.520594
1.083333	9.496442
1.125000	9.489358
1.166666	9.481951
1.208333	9.477121
1.250000	9.471003
1.291666	9.479053
1.333333	9.453614
1.375000	9.447495
1.416666	9.440411
1.458333	9.433004
1.500000	9.429140
1.541666	9.437513
1.583333	9.410141
1.625000	9.404345
1.666666	9.392430
1.708333	9.383413
1.750000	9.377939
1.791666	9.383091

Continued on next column

Continued from previous column

Time	Voltage
1.833333	9.360872
1.875000	9.353466
1.916666	9.345415
1.958333	9.339619
2.000000	9.329314
2.041666	9.321586
2.083333	9.309993
2.125000	9.301298
2.166666	9.286808
2.208333	9.282943
2.250000	9.277791
2.291666	9.264266
2.333333	9.250419
2.375000	9.243979
2.416666	9.234319
2.458333	9.225302
2.500000	9.213065
2.541666	9.201473
2.583333	9.196642
2.625000	9.183762
2.666666	9.173135
2.708333	9.161220
2.750000	9.150594

Continued on next column

Continued from previous column

Time	Voltage
2.791666	9.138357
2.833333	9.129018
2.875000	9.120002
2.916666	9.106477
2.958333	9.098427
3.000000	9.092630
3.041666	9.081682
3.083333	9.070089
3.124999	9.058818
3.166666	9.048836
3.208333	9.040141
3.249999	9.031769
3.291666	9.018244
3.333333	9.004397
3.374999	8.997635
3.416666	8.986364
3.458333	8.978636
3.499999	8.967687
3.541666	8.955772
3.583333	8.947722
3.624999	8.936451
3.666666	8.925180
3.708333	8.916164

Continued on next column

Continued from previous column

Time	Voltage
3.749999	8.909402
3.791666	8.884284
3.833333	8.885250
3.874999	8.874302
3.916666	8.866251
3.958333	8.855302
3.999999	8.847896
4.041666	8.820847
4.083333	8.824711
4.124999	8.813118
4.166666	8.803780
4.208333	8.795085
4.249999	8.782526
4.291666	8.757731
4.333333	8.760629
4.374999	8.749358
4.416666	8.740664
4.458333	8.730681
4.499999	8.722309
4.541666	8.698480
4.583333	8.699124
4.624999	8.689785
4.666666	8.680769

Continued on next column

Continued from previous column

Time	Voltage
4.708333	8.669176
4.749999	8.662414
4.791666	8.636974
4.833333	8.639550
4.874999	8.627958
4.916666	8.619263
4.958333	8.608958
4.999999	8.598976
5.041666	8.576757
5.083333	8.578689
5.124999	8.566452
5.166666	8.558724
5.208333	8.549063
5.249999	8.537148
5.291666	8.516539
5.333332	8.517505
5.374999	8.507201
5.416666	8.498506
5.458332	8.487880
5.499999	8.479185
5.541666	8.454390
5.583332	8.455678
5.624999	8.447949

Continued on next column

Continued from previous column

Time	Voltage
5.666666	8.441509
5.708332	8.431849
5.749999	8.422832
5.791666	8.396427
5.833332	8.398681
5.874999	8.388698
5.916666	8.382580
5.958332	8.371953
5.999999	8.363259
6.041666	8.340718
6.083332	8.342006
6.124999	8.331701
6.166666	8.317854
6.208332	8.313024
6.249999	8.302075
6.291666	8.277602
6.333332	8.279212
6.374999	8.266331
6.416666	8.256349
6.458332	8.250553
6.499999	8.242502
6.541666	8.213521
6.583332	8.216097

Continued on next column

Continued from previous column

Time	Voltage
6.624999	8.205470
6.666666	8.195488
6.708332	8.183251
6.749999	8.175201
6.791666	8.148795
6.833332	8.150083
6.874999	8.141711
6.916666	8.128508
6.958332	8.119813
6.999999	8.110797
7.041666	8.081493
7.083332	8.082781
7.124999	8.074409
7.166666	8.060884
7.208332	8.054766
7.249999	8.042529
7.291665	8.018700
7.333332	8.018700
7.374999	8.005819
7.416665	7.994227
7.458332	7.983600
7.499999	7.973618
7.541665	7.949144

Continued on next column

Continued from previous column

Time	Voltage
7.583332	7.949144
7.624999	7.937874
7.666665	7.925959
7.708332	7.915333
7.749999	7.899876
7.791665	7.884097
7.833332	7.877657
7.874999	7.864132
7.916665	7.854149
7.958332	7.844489
7.999999	7.830320
8.041665	7.814863
8.083332	7.807779
8.124999	7.793932
8.166665	7.785238
8.208332	7.771391
8.249999	7.762696
8.291665	7.739833
8.333332	7.739511
8.374999	7.726631
8.416665	7.718580
8.458332	7.702479
8.499999	7.691531

Continued on next column

Continued from previous column

Time	Voltage
8.541665	7.668667
8.583332	7.668667
8.624999	7.656431
8.666665	7.646770
8.708332	7.634856
8.749999	7.624873
8.791665	7.600078
8.833332	7.600400
8.874999	7.588163
8.916665	7.576893
8.958332	7.566266
8.999999	7.554674
9.041665	7.528268
9.083332	7.527946
9.124999	7.519574
9.166665	7.508303
9.208332	7.496711
9.249999	7.486728
9.291665	7.460001
9.333332	7.462577
9.374999	7.450662
9.416665	7.440358
9.458332	7.428443

Continued on next column

Continued from previous column

Time	Voltage
9.499998	7.417816
9.541665	7.392699
9.583332	7.393343
9.624998	7.381107
9.666665	7.373056
9.708332	7.360498
9.749998	7.351481
9.791665	7.323788
9.833332	7.326042
9.874998	7.314449
9.916665	7.301247
9.958332	7.291264
9.999998	7.284502
10.041665	7.258418
10.083332	7.260028
10.124998	7.248436
10.166665	7.237165
10.208332	7.227505
10.249998	7.219454
10.291665	7.189507
10.333332	7.193693
10.374998	7.183067
10.416665	7.168576

Continued on next column

Continued from previous column

Time	Voltage
10.458332	7.163102
10.499998	7.153763
10.541665	7.125104
10.583332	7.126070
10.624998	7.116731
10.666665	7.106749
10.708332	7.098698
10.749998	7.086784
10.791665	7.061344
10.833332	7.064565
10.874998	7.053294
10.916665	7.042346
10.958332	7.034939
10.999998	7.026889
11.041665	7.000483
11.083332	7.002093
11.124998	6.992111
11.166665	6.983417
11.208332	6.974078
11.249998	6.964096
11.291665	6.940266
11.333332	6.943809
11.374998	6.928996

Continued on next column

Continued from previous column

Time	Voltage
11.416665	6.922556
11.458331	6.914827
11.499998	6.906133
11.541665	6.882304
11.583331	6.883592
11.624998	6.872965
11.666665	6.865237
11.708331	6.854610
11.749998	6.846560
11.791665	6.822409
11.833331	6.822731
11.874998	6.812104
11.916665	6.803732
11.958331	6.795037
11.999998	6.785699
12.041665	6.759616
12.083331	6.761548
12.124998	6.749955
12.166665	6.739329
12.208331	6.730634
12.249998	6.723228
12.291665	6.698433
12.333331	6.699399

Continued on next column

Continued from previous column

Time	Voltage
12.374998	6.685552
12.416665	6.678468
12.458331	6.665909
12.499998	6.657859
12.541665	6.631453
12.583331	6.633063
12.624998	6.621793
12.666665	6.611488
12.708331	6.598286
12.749998	6.589591
12.791665	6.561898
12.833331	6.561576
12.874998	6.550305
12.916665	6.540645
12.958331	6.528730
12.999998	6.514562
13.041665	6.355808
13.083331	6.359672
13.124998	6.342283
13.166665	6.464649
13.208331	6.320386
13.249998	6.445328
13.291665	6.413771

Continued on next column

Continued from previous column

Time	Voltage
13.333331	6.413127
13.374998	6.280135
13.416665	6.249865
13.458331	6.232154
13.499998	6.229578
13.541664	6.187394
13.583331	6.193512
13.624998	6.178700
13.666664	6.164853
13.708331	6.151329
13.749998	6.140380
13.791664	6.109467
13.833331	6.110755
13.874998	6.090468
13.916664	6.075655
13.958331	6.065995
13.999998	6.046352
14.041664	6.018014
14.083331	6.022201
14.124998	6.002236
14.166664	5.989999
14.208331	5.977118
14.249998	5.964560

Continued on next column

Continued from previous column

Time	Voltage
14.291664	5.927528
14.333331	5.932358
14.374998	5.914970
14.416664	5.900157
14.458331	5.887920
14.499998	5.871498
14.541664	5.842194
14.583331	5.844770
14.624998	5.829314
14.666664	5.817399
14.708331	5.801942
14.749998	5.786808
14.791664	5.751708
14.833331	5.753962
14.874998	5.737539
14.916664	5.726913
14.958331	5.709846
14.999998	5.695034

Table A.3. Position Sensor Data for 800 RPM.

Time	Voltage
0.000000	9.808157
0.041667	9.813954
0.083333	9.812343
0.125000	9.806225
0.166667	9.793988
0.208333	9.790124
0.250000	9.790768
0.291667	9.787226
0.333333	9.790446
0.375000	9.786582
0.416667	9.773057
0.458333	9.768227
0.500000	9.761142
0.541667	9.752126
0.583333	9.753736
0.625000	9.753092
0.666667	9.739245
0.708333	9.733449
0.750000	9.727974
0.791667	9.724110
0.833333	9.726364

Continued on next column

Continued from previous column

Time	Voltage
0.875000	9.718958
0.916667	9.705433
0.958333	9.698026
1.000000	9.694806
1.041667	9.692552
1.083333	9.698670
1.125000	9.683858
1.166666	9.669367
1.208333	9.668401
1.250000	9.672265
1.291666	9.673875
1.333333	9.647469
1.375000	9.646825
1.416666	9.632334
1.458333	9.621064
1.500000	9.610115
1.541666	9.607539
1.583333	9.597878
1.625000	9.589506
1.666666	9.575659
1.708333	9.568897
1.750000	9.558592
1.791666	9.549253

Continued on next column

Continued from previous column

Time	Voltage
1.833333	9.542813
1.875000	9.536051
1.916666	9.516729
1.958333	9.508679
2.000000	9.497408
2.041666	9.490646
2.083333	9.484527
2.125000	9.477121
2.166666	9.459410
2.208333	9.456190
2.250000	9.444275
2.291666	9.433648
2.333333	9.425276
2.375000	9.420768
2.416666	9.402413
2.458333	9.384379
2.500000	9.372465
2.541666	9.364092
2.583333	9.350567
2.625000	9.350245
2.666666	9.328670
2.708333	9.314179
2.750000	9.300976

Continued on next column

Continued from previous column

Time	Voltage
2.791666	9.287452
2.833333	9.277791
2.875000	9.280045
2.916666	9.249131
2.958333	9.233352
3.000000	9.218862
3.041666	9.207269
3.083333	9.192778
3.124999	9.201473
3.166666	9.165084
3.208333	9.150272
3.249999	9.139001
3.291666	9.120968
3.333333	9.107443
3.374999	9.113239
3.416666	9.081360
3.458333	9.063649
3.499999	9.047870
3.541666	9.034667
3.583333	9.019854
3.624999	9.023396
3.666666	8.990872
3.708333	8.973161

Continued on next column

Continued from previous column

Time	Voltage
3.749999	8.956094
3.791666	8.941925
3.833333	8.922604
3.874999	8.909724
3.916666	8.896199
3.958333	8.880420
3.999999	8.861421
4.041666	8.843066
4.083333	8.826643
4.124999	8.811186
4.166666	8.797017
4.208333	8.776730
4.249999	8.759663
4.291666	8.742274
4.333333	8.729393
4.374999	8.713936
4.416666	8.698802
4.458333	8.681091
4.499999	8.664346
4.541666	8.643736
4.583333	8.626347
4.624999	8.609603
4.666666	8.595112

Continued on next column

Continued from previous column

Time	Voltage
4.708333	8.574825
4.749999	8.557114
4.791666	8.538437
4.833333	8.525878
4.874999	8.509455
4.916666	8.490778
4.958333	8.477575
4.999999	8.458898
5.041666	8.437967
5.083333	8.417358
5.124999	8.402545
5.166666	8.386122
5.208333	8.366157
5.249999	8.342972
5.291666	8.324939
5.333332	8.303041
5.374999	8.288229
5.416666	8.268586
5.458332	8.251197
5.499999	8.233486
5.541666	8.210300
5.583332	8.190979
5.624999	8.175201

Continued on next column

Continued from previous column

Time	Voltage
5.666666	8.159744
5.708332	8.139135
5.749999	8.120136
5.791666	8.101136
5.833332	8.080527
5.874999	8.047038
5.916666	8.046716
5.958332	8.025784
5.999999	8.000667
6.041666	7.979736
6.083332	7.962347
6.124999	7.924671
6.166666	7.925637
6.208332	7.904062
6.249999	7.884419
6.291666	7.861878
6.333332	7.841591
6.374999	7.804881
6.416666	7.806491
6.458332	7.787814
6.499999	7.762374
6.541666	7.739833
6.583332	7.720834

Continued on next column

Continued from previous column

Time	Voltage
6.624999	7.540827
6.666666	7.541793
6.708332	7.516354
6.749999	7.494778
6.791666	7.474491
6.833332	7.455170
6.874999	7.561114
6.916666	7.562402
6.958332	7.542437
6.999999	7.520218
7.041666	7.497355
7.083332	7.476101
7.124999	7.436171
7.166666	7.436493
7.208332	7.412020
7.249999	7.388513
7.291665	7.367582
7.333332	7.343753
7.374999	7.161813
7.416665	7.166322
7.458332	7.284824
7.499999	7.258418
7.541665	7.240707

Continued on next column

Continued from previous column

Time	Voltage
7.583332	7.217200
7.624999	7.180168
7.666665	7.182101
7.708332	7.158915
7.749999	7.135408
7.791665	7.111579
7.833332	7.086784
7.874999	6.892608
7.916665	6.895184
7.958332	7.023347
7.999999	7.000805
8.041665	6.977620
8.083332	6.805020
8.124999	6.757039
8.166665	6.760904
8.208332	6.892286
8.249999	6.869101
8.291665	6.846560
8.333332	6.824341
8.374999	6.785377
8.416665	6.789563
8.458332	6.760904
8.499999	6.736108

Continued on next column

Continued from previous column

Time	Voltage
8.541665	6.714211
8.583332	6.687484
8.624999	6.648842
8.666665	6.621793
8.708332	6.624047
8.749999	6.599896
8.791665	6.572846
8.833332	6.548373
8.874999	6.509731
8.916665	6.483648
8.958332	6.484936
8.999999	6.459175
9.041665	6.433092
9.083332	6.409263
9.124999	6.369011
9.166665	6.340029
9.208332	6.343250
9.249999	6.314912
9.291665	6.292371
9.333332	6.266288
9.374999	6.226036
9.416665	6.198021
9.458332	6.199953

Continued on next column

Continued from previous column

Time	Voltage
9.499998	6.174836
9.541665	6.151007
9.583332	6.125567
9.624998	6.080163
9.666665	6.051826
9.708332	6.055046
9.749998	6.025743
9.791665	5.998049
9.833332	5.979051
9.874998	5.933968
9.916665	5.761691
9.958332	5.764911
9.999998	5.733997
10.041665	5.716609
10.083332	5.688271
10.124998	5.642223
10.166665	5.616784
10.208332	5.623224
10.249998	5.594243
10.291665	5.564618
10.333332	5.539179
10.374998	5.492164
10.416665	5.464149

Continued on next column

Continued from previous column

Time	Voltage
10.458332	5.465437
10.499998	5.434846
10.541665	5.414559
10.583332	5.397170
10.624998	5.338886
10.666665	5.313447
10.708332	5.314413
10.749998	5.282533
10.791665	5.260314
10.833332	5.228757
10.874998	5.184641
10.916665	5.161456
10.958332	5.163066
10.999998	5.133763
11.041665	5.106392
11.083332	5.076766
11.124998	5.037159
11.166665	5.017516
11.208332	5.016550
11.249998	4.987568
11.291665	4.977908
11.333332	4.956977
11.374998	4.881626

Continued on next column

Continued from previous column

Time	Voltage
11.416665	4.858763
11.458331	4.858119
11.499998	4.971790
11.541665	4.943453
11.583331	4.912861
11.624998	4.871643
11.666665	4.843628
11.708331	4.845560
11.749998	4.817223
11.791665	4.787920
11.833331	4.631743
11.874998	4.716111
11.916665	4.542224
11.958331	4.542224
11.999998	4.662013
12.041665	4.498108
12.083331	4.467194
12.124998	4.432739
12.166665	4.526767
12.208331	4.527411
12.249998	4.502294
12.291665	4.472347
12.333331	4.443043

Continued on next column

Continued from previous column

Time	Voltage
12.374998	4.399894
12.416665	4.370912
12.458331	4.342253
12.499998	4.345795
12.541665	4.311018
12.583331	4.289443
12.624998	4.071762
12.666665	4.037629
12.708331	4.011546
12.749998	4.016376
12.791665	4.018630
12.833331	3.963888
12.874998	3.948753
12.916665	3.937805
12.958331	3.894333
12.999998	3.894333
13.041665	3.860200
13.083331	3.840879
13.124998	3.779375
13.166665	3.778409
13.208331	3.872436
13.249998	3.874046
13.291665	3.727853

Continued on next column

Continued from previous column

Time	Voltage
13.333331	3.816084
13.374998	3.649603
13.416665	3.742021
13.458331	3.710142
13.499998	3.707888
13.541664	3.680517
13.583331	3.658942
13.624998	3.607742
13.666664	3.577151
13.708331	3.547203
13.749998	3.547203
13.791664	3.519510
13.833331	3.491817
13.874998	3.318575
13.916664	3.242902
13.958331	3.220361
13.999998	3.220683
14.041664	3.224869
14.083331	3.159178
14.124998	3.112165
14.166664	3.113453
14.208331	3.084472
14.249998	3.085760

Continued on next column

Continued from previous column

Time	Voltage
14.291664	3.056779
14.333331	3.024899
14.374998	2.954057
14.416664	2.950837
14.458331	2.893196
14.499998	2.897061
14.541664	2.887722
14.583331	2.854555
14.624998	2.805287
14.666664	2.777272
14.708331	2.748291
14.749998	2.752477
14.791664	2.728970
14.833331	2.705141
14.874998	2.668754
14.916664	2.769544
14.958331	2.734766
14.999998	2.740885

Table A.4. Position Sensor Data for 900 RPM.

Time	Voltage
0.000000	9.810733
0.041667	9.814598
0.083333	9.799785
0.125000	9.806225
0.166667	9.806225
0.208333	9.810733
0.250000	9.814920
0.291667	9.815886
0.333333	9.801073
0.375000	9.805259
0.416667	9.807191
0.458333	9.812343
0.500000	9.816530
0.541667	9.819106
0.583333	9.805581
0.625000	9.808479
0.666667	9.808801
0.708333	9.813954
0.750000	9.809445
0.791667	9.812343
0.833333	9.800429

Continued on next column

Continued from previous column

Time	Voltage
0.875000	9.804293
0.916667	9.797209
0.958333	9.799141
1.000000	9.797209
1.041667	9.798497
1.083333	9.784972
1.125000	9.781430
1.166666	9.782074
1.208333	9.776921
1.250000	9.774989
1.291666	9.778853
1.333333	9.765329
1.375000	9.758244
1.416666	9.753092
1.458333	9.748906
1.500000	9.743753
1.541666	9.741177
1.583333	9.731194
1.625000	9.724110
1.666666	9.720568
1.708333	9.711229
1.750000	9.707365
1.791666	9.700925

Continued on next column

Continued from previous column

Time	Voltage
1.833333	9.686756
1.875000	9.682891
1.916666	9.677095
1.958333	9.667435
2.000000	9.656808
2.041666	9.655198
2.083333	9.641673
2.125000	9.631690
2.166666	9.624284
2.208333	9.614301
2.250000	9.606895
2.291666	9.598844
2.333333	9.585642
2.375000	9.572439
2.416666	9.563422
2.458333	9.553762
2.500000	9.548609
2.541666	9.536051
2.583333	9.522848
2.625000	9.509645
2.666666	9.497408
2.708333	9.487426
2.750000	9.474223

Continued on next column

Continued from previous column

Time	Voltage
2.791666	9.467782
2.833333	9.455224
2.875000	9.438801
2.916666	9.427208
2.958333	9.413039
3.000000	9.401124
3.041666	9.387600
3.083333	9.374397
3.124999	9.359262
3.166666	9.345737
3.208333	9.329636
3.249999	9.318688
3.291666	9.305485
3.333333	9.291960
3.374999	9.272317
3.416666	9.259758
3.458333	9.240759
3.499999	9.224658
3.541666	9.211777
3.583333	9.199540
3.624999	9.177321
3.666666	9.160254
3.708333	9.143187

Continued on next column

Continued from previous column

Time	Voltage
3.749999	9.124510
3.791666	9.106477
3.833333	9.092308
3.874999	9.074597
3.916666	9.054954
3.958333	9.035955
3.999999	9.016312
4.041666	8.998923
4.083333	8.985398
4.124999	8.963823
4.166666	8.941281
4.208333	8.920350
4.249999	8.902961
4.291666	8.880742
4.333333	8.866573
4.374999	8.846286
4.416666	8.826965
4.458333	8.806034
4.499999	8.784458
4.541666	8.761273
4.583333	8.747748
4.624999	8.725207
4.666666	8.702988

Continued on next column

Continued from previous column

Time	Voltage
4.708333	8.680125
4.749999	8.656617
4.791666	8.638906
4.833333	8.624093
4.874999	8.598332
4.916666	8.574503
4.958333	8.551317
4.999999	8.529742
5.041666	8.505913
5.083333	8.493032
5.124999	8.467593
5.166666	8.444085
5.208333	8.421222
5.249999	8.397071
5.291666	8.375495
5.333332	8.361005
5.374999	8.334277
5.416666	8.308194
5.458332	8.285331
5.499999	8.258603
5.541666	8.237028
5.583332	8.224791
5.624999	8.198064

Continued on next column

Continued from previous column

Time	Voltage
5.666666	8.169726
5.708332	8.146219
5.749999	8.120780
5.791666	8.097916
5.833332	8.082459
5.874999	8.056376
5.916666	8.029649
5.958332	8.003243
5.999999	7.976194
6.041666	7.952042
6.083332	7.939806
6.124999	7.910180
6.166666	7.885063
6.208332	7.857047
6.249999	7.827744
6.291666	7.803593
6.333332	7.760764
6.374999	7.763662
6.416666	7.735969
6.458332	7.707310
6.499999	7.677362
6.541666	7.652245
6.583332	7.607484

Continued on next column

Continued from previous column

Time	Voltage
6.624999	7.610382
6.666666	7.577215
6.708332	7.551775
6.749999	7.525692
6.791666	7.497033
6.833332	7.451628
6.874999	7.454526
6.916666	7.423613
6.958332	7.394309
6.999999	7.366616
7.041666	7.338922
7.083332	7.293518
7.124999	7.294484
7.166666	7.265181
7.208332	7.235233
7.249999	7.203032
7.291665	7.177270
7.333332	7.133798
7.374999	7.134764
7.416665	7.102885
7.458332	7.073903
7.499999	7.044922
7.541665	7.015940

Continued on next column

Continued from previous column

Time	Voltage
7.583332	6.970214
7.624999	6.970214
7.666665	6.940588
7.708332	6.913539
7.749999	6.881338
7.791665	6.853966
7.833332	6.805986
7.874999	6.806308
7.916665	6.633707
7.958332	6.617285
7.999999	6.570270
8.041665	6.545475
8.083332	6.491699
8.124999	6.491699
8.166665	6.607302
8.208332	6.429550
8.249999	6.406687
8.291665	6.370943
8.333332	6.327149
8.374999	6.324251
8.416665	6.298167
8.458332	6.262102
8.499999	6.223460

Continued on next column

Continued from previous column

Time	Voltage
8.541665	6.200919
8.583332	6.146498
8.624999	6.149074
8.666665	6.117839
8.708332	6.083383
8.749999	6.047640
8.791665	6.021879
8.833332	5.969712
8.874999	5.972288
8.916665	5.938799
8.958332	5.900479
8.999999	5.871820
9.041665	5.843482
9.083332	5.787130
9.124999	5.791638
9.166665	5.756538
9.208332	5.724015
9.249999	5.690525
9.291665	5.671204
9.333332	5.604548
9.374999	5.608090
9.416665	5.572990
9.458332	5.544009

Continued on next column

Continued from previous column

Time	Voltage
9.499998	5.512451
9.541665	5.461251
9.583332	5.427118
9.624998	5.395238
9.666665	5.395882
9.708332	5.364003
9.749998	5.335022
9.791665	5.420999
9.833332	5.383968
9.874998	5.350478
9.916665	5.350800
9.958332	5.319243
9.999998	5.286397
10.041665	5.231333
10.083332	5.200098
10.124998	5.166608
10.166665	5.166286
10.208332	5.131509
10.249998	5.099951
10.291665	5.046497
10.333332	5.013652
10.374998	4.975976
10.416665	4.976620

Continued on next column

Continued from previous column

Time	Voltage
10.458332	4.946029
10.499998	4.908031
10.541665	4.856831
10.583332	4.825273
10.624998	4.787598
10.666665	4.788886
10.708332	4.755719
10.749998	4.719331
10.791665	4.671029
10.833332	4.634641
10.874998	4.595678
10.916665	4.601796
10.958332	4.566375
10.999998	4.527411
11.041665	4.479109
11.083332	4.443365
11.124998	4.406012
11.166665	4.409554
11.208332	4.375743
11.249998	4.339033
11.291665	4.288155
11.333332	4.251768
11.374998	4.216668

Continued on next column

Continued from previous column

Time	Voltage
11.416665	4.221820
11.458331	4.183823
11.499998	3.976446
11.541665	3.970328
11.583331	3.941025
11.624998	4.024104
11.666665	4.029901
11.708331	3.992225
11.749998	3.958092
11.791665	3.793543
11.833331	3.870182
11.874998	3.833473
11.916665	3.837337
11.958331	3.800305
11.999998	3.764884
12.041665	3.713684
12.083331	3.675042
12.124998	3.639621
12.166665	3.643485
12.208331	3.605488
12.249998	3.572642
12.291665	3.390705
12.333331	3.346912

Continued on next column

Continued from previous column

Time	Voltage
12.374998	3.311490
12.416665	3.232919
12.458331	3.232919
12.499998	3.235495
12.541665	3.181397
12.583331	3.115063
12.624998	3.104758
12.666665	3.066439
12.708331	3.069981
12.749998	3.015561
12.791665	2.955023
12.833331	2.920245
12.874998	2.883536
12.916665	2.850691
12.958331	2.855521
12.999998	2.824930
13.041665	2.773408
13.083331	2.741529
13.124998	2.718666
13.166665	2.814625
13.208331	2.819778
13.249998	2.652009
13.291665	2.597589

Continued on next column

Continued from previous column

Time	Voltage
13.333331	2.555406
13.374998	2.517408
13.416665	2.480055
13.458331	2.485207
13.499998	2.449142
13.541664	2.394400
13.583331	2.358013
13.624998	2.333540
13.666664	2.298762
13.708331	2.302949
13.749998	2.389570
13.791664	2.340624
13.833331	2.306169
13.874998	2.265917
13.916664	2.231462
13.958331	2.235970
13.999998	2.200227
14.041664	2.149349
14.083331	2.112962
14.124998	2.074642
14.166664	2.041797
14.208331	2.045661
14.249998	2.007664

Continued on next column

Continued from previous column

Time	Voltage
14.291664	1.960328
14.333331	1.923297
14.374998	1.886910
14.416664	1.852776
14.458331	1.856319
14.499998	1.821219
14.541664	1.775816
14.583331	1.738462
14.624998	1.704651
14.666664	1.671484
14.708331	1.673094
14.749998	1.639927
14.791664	1.592913
14.833331	1.557492
14.874998	1.521105
14.916664	1.494378
14.958331	1.494700
14.999998	1.467651

Table A.5. Position Sensor Data for 1000 RPM.

Time	Voltage
0.000000	9.812665
0.041667	9.793344
0.083333	9.787226
0.125000	9.788514
0.166667	9.782074
0.208333	9.776599
0.250000	9.779175
0.291667	9.756634
0.333333	9.751804
0.375000	9.741499
0.416667	9.736669
0.458333	9.729262
0.500000	9.732161
0.541667	9.710907
0.583333	9.698992
0.625000	9.690620
0.666667	9.681281
0.708333	9.678061
0.750000	9.682247
0.791667	9.655198
0.833333	9.639741

Continued on next column

Continued from previous column

Time	Voltage
0.875000	9.629758
0.916667	9.616555
0.958333	9.612047
1.000000	9.616555
1.041667	9.584031
1.083333	9.572439
1.125000	9.560202
1.166666	9.545389
1.208333	9.533152
1.250000	9.539271
1.291666	9.507391
1.333333	9.491290
1.375000	9.478731
1.416666	9.466816
1.458333	9.451681
1.500000	9.458766
1.541666	9.420124
1.583333	9.404023
1.625000	9.389210
1.666666	9.371499
1.708333	9.356042
1.750000	9.364736
1.791666	9.325128

Continued on next column

Continued from previous column

Time	Voltage
1.833333	9.305163
1.875000	9.286486
1.916666	9.270063
1.958333	9.248487
2.000000	9.255572
2.041666	9.218218
2.083333	9.199862
2.125000	9.177965
2.166666	9.155424
2.208333	9.135137
2.250000	9.143187
2.291666	9.104223
2.333333	9.075563
2.375000	9.054632
2.416666	9.032413
2.458333	9.008583
2.500000	8.996025
2.541666	8.969941
2.583333	8.952552
2.625000	8.925180
2.666666	8.897487
2.708333	8.875268
2.750000	8.834371

Continued on next column

Continued from previous column

Time	Voltage
2.791666	8.837591
2.833333	8.810542
2.875000	8.786069
2.916666	8.759985
2.958333	8.736156
3.000000	8.694937
3.041666	8.696225
3.083333	8.667888
3.124999	8.639872
3.166666	8.611535
3.208333	8.588671
3.249999	8.547775
3.291666	8.548419
3.333333	8.519759
3.374999	8.491744
3.416666	8.460186
3.458333	8.432815
3.499999	8.391274
3.541666	8.392884
3.583333	8.364225
3.624999	8.333955
3.666666	8.302719
3.708333	8.275348

Continued on next column

Continued from previous column

Time	Voltage
3.749999	8.227689
3.791666	8.230588
3.833333	8.197742
3.874999	8.169082
3.916666	8.137846
3.958333	8.106933
3.999999	8.057986
4.041666	8.060884
4.083333	8.026106
4.124999	7.994549
4.166666	7.962025
4.208333	7.932721
4.249999	7.886995
4.291666	7.886995
4.333333	7.851895
4.374999	7.820015
4.416666	7.787814
4.458333	7.751426
4.499999	7.702801
4.541666	7.706343
4.583333	7.669312
4.624999	7.636144
4.666666	7.603942

Continued on next column

Continued from previous column

Time	Voltage
4.708333	7.567554
4.749999	7.519896
4.791666	7.520218
4.833333	7.482220
4.874999	7.448086
4.916666	7.412664
4.958333	7.379497
4.999999	7.329584
5.041666	7.330228
5.083333	7.292874
5.124999	7.261639
5.166666	7.221064
5.208333	7.187897
5.249999	7.135730
5.291666	7.137984
5.333332	7.098376
5.374999	7.062955
5.416666	7.025601
5.458332	6.991467
5.499999	6.939300
5.541666	6.938978
5.583332	6.900658
5.624999	6.867813

Continued on next column

Continued from previous column

Time	Voltage
5.666666	6.826917
5.708332	6.787631
5.749999	6.735464
5.791666	6.568660
5.833332	6.571880
5.874999	6.520036
5.916666	6.477530
5.958332	6.446938
5.999999	6.386078
6.041666	6.344216
6.083332	6.349046
6.124999	6.309116
6.166666	6.273694
6.208332	6.235374
6.249999	6.180632
6.291666	6.143922
6.333332	6.147142
6.374999	6.097874
6.416666	6.058910
6.458332	6.020912
6.499999	5.963594
6.541666	5.921732
6.583332	5.925274

Continued on next column

Continued from previous column

Time	Voltage
6.624999	5.885344
6.666666	5.837686
6.708332	5.802264
6.749999	5.743980
6.791666	5.705016
6.833332	5.706304
6.874999	5.659934
6.916666	5.622258
6.958332	5.583617
6.999999	5.523722
7.041666	5.484436
7.083332	5.487012
7.124999	5.443218
7.166666	5.407153
7.208332	5.363681
7.249999	5.311514
7.291665	5.270297
7.333332	5.269653
7.374999	5.228113
7.416665	5.198166
7.458332	5.157592
7.499999	5.101239
7.541665	5.186895

Continued on next column

Continued from previous column

Time	Voltage
7.583332	5.187539
7.624999	5.146321
7.666665	5.103493
7.708332	5.063242
7.749999	5.004313
7.791665	4.959875
7.833332	4.958265
7.874999	4.918335
7.916665	4.877440
7.958332	4.833324
7.999999	4.776005
8.041665	4.731568
8.083332	4.732212
8.124999	4.690672
8.166665	4.645590
8.208332	4.603406
8.249999	4.550596
8.291665	4.502938
8.333332	4.503582
8.374999	4.463330
8.416665	4.414384
8.458332	4.372523
8.499999	4.315526

Continued on next column

Continued from previous column

Time	Voltage
8.541665	4.269156
8.583332	4.225363
8.624999	4.227617
8.666665	4.003496
8.708332	3.965176
8.749999	3.947465
8.791665	3.910434
8.833332	3.867928
8.874999	3.870826
8.916665	3.952940
8.958332	3.913010
8.999999	3.730429
9.041665	3.804814
9.083332	3.763274
9.124999	3.763918
9.166665	3.719480
9.208332	3.678263
9.249999	3.614182
9.291665	3.568134
9.333332	3.525951
9.374999	3.525307
9.416665	3.482479
9.458332	3.314710

Continued on next column

Continued from previous column

Time	Voltage
9.499998	3.254172
9.541665	3.198142
9.583332	3.150484
9.624998	3.151128
9.666665	3.108623
9.708332	3.066761
9.749998	2.998172
9.791665	2.931194
9.833332	2.886756
9.874998	2.884180
9.916665	2.845539
9.958332	2.813337
9.999998	2.756341
10.041665	2.721242
10.083332	2.686787
10.124998	2.686787
10.166665	2.649111
10.208332	2.603386
10.249998	2.538661
10.291665	2.492614
10.333332	2.446244
10.374998	2.448176
10.416665	2.402772

Continued on next column

Continued from previous column

Time	Voltage
10.458332	2.366063
10.499998	2.313253
10.541665	2.270425
10.583332	2.352538
10.624998	2.355436
10.666665	2.314219
10.708332	2.269137
10.749998	2.209565
10.791665	2.168026
10.833332	2.124232
10.874998	2.082371
10.916665	2.084947
10.958332	2.042441
10.999998	1.986089
11.041665	1.941652
11.083332	1.898180
11.124998	1.856641
11.166665	1.858573
11.208332	1.816067
11.249998	1.759393
11.291665	1.717532
11.333332	1.674704
11.374998	1.632521

Continued on next column

Continued from previous column

Time	Voltage
11.416665	1.634775
11.458331	1.594201
11.499998	1.539137
11.541665	1.495344
11.583331	1.451550
11.624998	1.414841
11.666665	1.415163
11.708331	1.376200
11.749998	1.325000
11.791665	1.287003
11.833331	1.251581
11.874998	1.221634
11.916665	1.224210
11.958331	1.198772
11.999998	1.153046
12.041665	1.124387
12.083331	1.097338
12.124998	1.074797
12.166665	1.077695
12.208331	1.055799
12.249998	1.019089
12.291665	0.994939
12.333331	0.976906

Continued on next column

Continued from previous column

Time	Voltage
12.374998	0.959195
12.416665	0.961449
12.458331	0.947603
12.499998	0.915724
12.541665	0.900267
12.583331	0.889963
12.624998	0.878371
12.666665	0.881913
12.708331	0.874506
12.749998	0.850356
12.791665	0.842305
12.833331	0.838441
12.874998	0.832967
12.916665	0.836187
12.958331	0.833611
12.999998	0.813324
13.041665	0.811070
13.083331	0.810748
13.124998	0.807528
13.166665	0.812358
13.208331	0.812036
13.249998	0.794326
13.291665	0.795292

Continued on next column

Continued from previous column

Time	Voltage
13.333331	0.795936
13.374998	0.795614
13.416665	0.801410
13.458331	0.803020
13.499998	0.787563
13.541664	0.789818
13.583331	0.790784
13.624998	0.795614
13.666664	0.797868
13.708331	0.802054
13.749998	0.789818
13.791664	0.788851
13.833331	0.791428
13.874998	0.793360
13.916664	0.797868
13.958331	0.801088
13.999998	0.786919
14.041664	0.790462
14.083331	0.790784
14.124998	0.794970
14.166664	0.796902
14.208331	0.799800
14.249998	0.785631

Continued on next column

Continued from previous column

Time	Voltage
14.291664	0.785953
14.333331	0.788529
14.374998	0.790140
14.416664	0.792716
14.458331	0.796258
14.499998	0.782733
14.541664	0.782089
14.583331	0.783377
14.624998	0.786919
14.666664	0.792072
14.708331	0.793360
14.749998	0.780479
14.791664	0.781767
14.833331	0.784343
14.874998	0.786275
14.916664	0.790140
14.958331	0.791750
14.999998	0.778547

Table A.6. Position Sensor Data for 1100 RPM.

Time	Voltage
0.000000	9.755990
0.041667	9.752448
0.083333	9.747939
0.125000	9.741499
0.166667	9.735059
0.208333	9.722178
0.250000	9.713161
0.291667	9.706721
0.333333	9.694806
0.375000	9.689654
0.416667	9.682891
0.458333	9.668723
0.500000	9.662604
0.541667	9.643927
0.583333	9.633622
0.625000	9.615267
0.666667	9.609793
0.708333	9.595302
0.750000	9.575337
0.791667	9.567930
0.833333	9.553762

Continued on next column

Continued from previous column

Time	Voltage
0.875000	9.538627
0.916667	9.518017
0.958333	9.503527
1.000000	9.487748
1.041667	9.471003
1.083333	9.449427
1.125000	9.436225
1.166666	9.417547
1.208333	9.403701
1.250000	9.387278
1.291666	9.369567
1.333333	9.342195
1.375000	9.326094
1.416666	9.300976
1.458333	9.287130
1.500000	9.262012
1.541666	9.243013
1.583333	9.213387
1.625000	9.193100
1.666666	9.167339
1.708333	9.153492
1.750000	9.130628
1.791666	9.103257

Continued on next column

Continued from previous column

Time	Voltage
1.833333	9.077173
1.875000	9.049480
1.916666	9.024040
1.958333	9.009871
2.000000	8.982178
2.041666	8.952552
2.083333	8.924536
2.125000	8.896843
2.166666	8.870437
2.208333	8.855947
2.250000	8.824389
2.291666	8.795407
2.333333	8.763849
2.375000	8.731969
2.416666	8.706530
2.458333	8.692039
2.500000	8.653397
2.541666	8.624415
2.583333	8.594146
2.625000	8.560334
2.666666	8.526844
2.708333	8.514607
2.750000	8.479829

Continued on next column

Continued from previous column

Time	Voltage
2.791666	8.447627
2.833333	8.411883
2.875000	8.378394
2.916666	8.342972
2.958333	8.328481
3.000000	8.294025
3.041666	8.258603
3.083333	8.221249
3.124999	8.186793
3.166666	8.150083
3.208333	8.137846
3.249999	8.099526
3.291666	8.058952
3.333333	8.024496
3.374999	7.986820
3.416666	7.953009
3.458333	7.937874
3.499999	7.895689
3.541666	7.859946
3.583333	7.818405
3.624999	7.779763
3.666666	7.742731
3.708333	7.686378

Continued on next column

Continued from previous column

Time	Voltage
3.749999	7.685090
3.791666	7.647414
3.833333	7.606518
3.874999	7.565944
3.916666	7.526980
3.958333	7.467729
3.999999	7.472237
4.041666	7.430375
4.083333	7.387547
4.124999	7.344397
4.166666	7.306077
4.208333	7.248436
4.249999	7.249080
4.291666	7.204642
4.333333	7.162780
4.374999	7.121239
4.416666	7.079055
4.458333	7.022058
4.499999	7.023347
4.541666	6.977298
4.583333	6.930606
4.624999	6.892608
4.666666	6.848492

Continued on next column

Continued from previous column

Time	Voltage
4.708333	6.787309
4.749999	6.788919
4.791666	6.745447
4.833333	6.699077
4.874999	6.657859
4.916666	6.472700
4.958333	6.404754
4.999999	6.409585
5.041666	6.360960
5.083333	6.315878
5.124999	6.270152
5.166666	6.228934
5.208333	6.158735
5.249999	6.161955
5.291666	6.114297
5.333332	6.069537
5.374999	6.022845
5.416666	5.974220
5.458332	5.908529
5.499999	5.913360
5.541666	5.861515
5.583332	5.815789
5.624999	5.768131

Continued on next column

Continued from previous column

Time	Voltage
5.666666	5.722083
5.708332	5.655748
5.749999	5.658646
5.791666	5.606158
5.833332	5.562686
5.874999	5.511807
5.916666	5.466081
5.958332	5.405543
5.999999	5.350156
6.041666	5.350478
6.083332	5.307328
6.124999	5.261280
6.166666	5.225537
6.208332	5.157592
6.249999	5.116374
6.291666	5.119272
6.333332	5.191403
6.374999	5.138271
6.416666	5.094155
6.458332	5.024600
6.499999	4.972434
6.541666	4.974366
6.583332	4.925098

Continued on next column

Continued from previous column

Time	Voltage
6.624999	4.874220
6.666666	4.829138
6.708332	4.756685
6.749999	4.704518
6.791666	4.708383
6.833332	4.657182
6.874999	4.604694
6.916666	4.558002
6.958332	4.488769
6.999999	4.431773
7.041666	4.436925
7.083332	4.385403
7.124999	4.331627
7.166666	4.282681
7.208332	4.036985
7.249999	3.984175
7.291665	3.988039
7.333332	3.947465
7.374999	4.059526
7.416665	4.027002
7.458332	3.939737
7.499999	3.886283
7.541665	3.891113

Continued on next column

Continued from previous column

Time	Voltage
7.583332	3.838303
7.624999	3.785815
7.666665	3.719158
7.708332	3.662806
7.749999	3.613216
7.791665	3.612572
7.833332	3.557508
7.874999	3.508562
7.916665	3.304406
7.958332	3.248054
7.999999	3.190736
8.041665	3.132451
8.083332	3.132773
8.124999	3.083184
8.166665	2.986258
8.208332	2.928940
8.249999	2.875808
8.291665	2.827184
8.333332	2.829438
8.374999	2.785644
8.416665	2.719310
8.458332	2.676804
8.499999	2.625282

Continued on next column

Continued from previous column

Time	Voltage
8.541665	2.565710
8.583332	2.568286
8.624999	2.513222
8.666665	2.437227
8.708332	2.381197
8.749999	2.335472
8.791665	2.284272
8.833332	2.287492
8.874999	2.359623
8.916665	2.289746
8.958332	2.234038
8.999999	2.178008
9.041665	2.120368
9.083332	2.124876
9.124999	2.069168
9.166665	2.000258
9.208332	1.945194
9.249999	1.887876
9.291665	1.831524
9.333332	1.836032
9.374999	1.779358
9.416665	1.707549
9.458332	1.653773

Continued on next column

Continued from previous column

Time	Voltage
9.499998	1.596777
9.541665	1.543645
9.583332	1.548476
9.624998	1.490836
9.666665	1.421281
9.708332	1.367505
9.749998	1.313085
9.791665	1.260920
9.833332	1.265428
9.874998	1.218092
9.916665	1.158520
9.958332	1.113761
9.999998	1.074153
10.041665	1.037444
10.083332	1.040664
10.124998	1.007175
10.166665	0.962093
10.208332	0.929248
10.249998	0.901233
10.291665	0.878693
10.333332	0.854220
10.374998	0.857118
10.416665	0.820409

Continued on next column

Continued from previous column

Time	Voltage
10.458332	0.797868
10.499998	0.781767
10.541665	0.764379
10.583332	0.747956
10.624998	0.750210
10.666665	0.723483
10.708332	0.714145
10.749998	0.701265
10.791665	0.695146
10.833332	0.691604
10.874998	0.694502
10.916665	0.684198
10.958332	0.687096
10.999998	0.689672
11.041665	0.692892
11.083332	0.699010
11.124998	0.703519
11.166665	0.694824
11.208332	0.695468
11.249998	0.698688
11.291665	0.697722
11.333332	0.700621
11.374998	0.704807

Continued on next column

Continued from previous column

Time	Voltage
11.416665	0.691604
11.458331	0.692892
11.499998	0.695790
11.541665	0.694180
11.583331	0.698044
11.624998	0.703519
11.666665	0.689350
11.708331	0.693536
11.749998	0.694502
11.791665	0.699976
11.833331	0.706095
11.874998	0.709637
11.916665	0.699010
11.958331	0.702875
11.999998	0.706739
12.041665	0.715755
12.083331	0.721873
12.124998	0.724127
12.166665	0.715755
12.208331	0.723805
12.249998	0.733466
12.291665	0.741838
12.333331	0.752786

Continued on next column

Continued from previous column

Time	Voltage
12.374998	0.755362
12.416665	0.752786
12.458331	0.765023
12.499998	0.774361
12.541665	0.789818
12.583331	0.806240
12.624998	0.809138
12.666665	0.808816
12.708331	0.822985
12.749998	0.839407
12.791665	0.853254
12.833331	0.871286
12.874998	0.875150
12.916665	0.878049
12.958331	0.895437
12.999998	0.911538
13.041665	0.932146
13.083331	0.952433
13.124998	0.954687
13.166665	0.956619
13.208331	0.975940
13.249998	0.996549
13.291665	1.017479

Continued on next column

Continued from previous column

Time	Voltage
13.333331	1.020377
13.374998	1.039698
13.416665	1.047104
13.458331	1.066425
13.499998	1.083492
13.541664	1.110540
13.583331	1.112473
13.624998	1.135013
13.666664	1.142098
13.708331	1.164316
13.749998	1.189111
13.791664	1.213584
13.833331	1.217448
13.874998	1.242565
13.916664	1.252225
13.958331	1.276376
13.999998	1.303103
14.041664	1.331440
14.083331	1.331440
14.124998	1.360743
14.166664	1.374590
14.208331	1.403249
14.249998	1.431586

Continued on next column

Continued from previous column

Time	Voltage
14.291664	1.459601
14.333331	1.461855
14.374998	1.495666
14.416664	1.511444
14.458331	1.541069
14.499998	1.573593
14.541664	1.600963
14.583331	1.604506
14.624998	1.639605
14.666664	1.654417
14.708331	1.682432
14.749998	1.715278
14.791664	1.742648
14.833331	1.745869
14.874998	1.778392
14.916664	1.787730
14.958331	1.814779
14.999998	1.840540

Table A.7. Position Sensor Data for 1200 RPM.

Time	Voltage
0.000000	9.790446
0.041667	9.776599
0.083333	9.770481
0.125000	9.762108
0.166667	9.755990
0.208333	9.751482
0.250000	9.742787
0.291667	9.729262
0.333333	9.717670
0.375000	9.710907
0.416667	9.699314
0.458333	9.688366
0.500000	9.678383
0.541667	9.666146
0.583333	9.654232
0.625000	9.641351
0.666667	9.627826
0.708333	9.610759
0.750000	9.599166
0.791667	9.584031
0.833333	9.568253

Continued on next column

Continued from previous column

Time	Voltage
0.875000	9.551830
0.916667	9.537017
0.958333	9.515763
1.000000	9.501916
1.041667	9.487104
1.083333	9.465206
1.125000	9.446529
1.166666	9.424632
1.208333	9.402413
1.250000	9.388244
1.291666	9.374397
1.333333	9.346381
1.375000	9.322874
1.416666	9.301298
1.458333	9.274571
1.500000	9.258148
1.541666	9.238827
1.583333	9.208235
1.625000	9.184728
1.666666	9.156068
1.708333	9.127408
1.750000	9.113561
1.791666	9.089410

Continued on next column

Continued from previous column

Time	Voltage
1.833333	9.055598
1.875000	9.026294
1.916666	8.997635
1.958333	8.966399
2.000000	8.957382
2.041666	8.922926
2.083333	8.888148
2.125000	8.853692
2.166666	8.822135
2.208333	8.789611
2.250000	8.757731
2.291666	8.742596
2.333333	8.708462
2.375000	8.671108
2.416666	8.634720
2.458333	8.600264
2.500000	8.565486
2.541666	8.550351
2.583333	8.511387
2.625000	8.474999
2.666666	8.436357
2.708333	8.398359
2.750000	8.357462

Continued on next column

Continued from previous column

Time	Voltage
2.791666	8.343938
2.833333	8.305296
2.875000	8.266653
2.916666	8.223825
2.958333	8.184861
3.000000	8.145575
3.041666	8.129474
3.083333	8.087934
3.124999	8.043495
3.166666	8.005175
3.208333	7.957195
3.249999	7.920163
3.291666	7.905672
3.333333	7.858657
3.374999	7.811965
3.416666	7.769459
3.458333	7.725020
3.499999	7.681870
3.541666	7.617789
3.583333	7.616501
3.624999	7.576571
3.666666	7.528590
3.708333	7.480288

Continued on next column

Continued from previous column

Time	Voltage
3.749999	7.437782
3.791666	7.375954
3.833333	7.372090
3.874999	7.323144
3.916666	7.277095
3.958333	7.230725
3.999999	7.184999
4.041666	7.115765
4.083333	7.118019
4.124999	7.070039
4.166666	7.023669
4.208333	6.972146
4.249999	6.926098
4.291666	6.861373
4.333333	6.861051
4.374999	6.809528
4.416666	6.758650
4.458333	6.707127
4.499999	6.659147
4.541666	6.588303
4.583333	6.590235
4.624999	6.539035
4.666666	6.348080

Continued on next column

Continued from previous column

Time	Voltage
4.708333	6.435990
4.749999	6.246001
4.791666	6.170327
4.833333	6.171293
4.874999	6.118483
4.916666	6.069215
4.958333	6.009642
4.999999	5.963272
5.041666	5.886954
5.083333	5.891463
5.124999	5.833178
5.166666	5.774571
5.208333	5.723693
5.249999	5.714998
5.291666	5.597141
5.333332	5.544653
5.374999	5.547873
5.416666	5.490232
5.458332	5.437100
5.499999	5.367223
5.541666	5.310870
5.583332	5.256772
5.624999	5.257094

Continued on next column

Continued from previous column

Time	Voltage
5.666666	5.206216
5.708332	5.156304
5.749999	5.088681
5.791666	5.157270
5.833332	5.103171
5.874999	5.103493
5.916666	5.047463
5.958332	4.989823
5.999999	4.917047
6.041666	4.861017
6.083332	4.804987
6.124999	4.804987
6.166666	4.748312
6.208332	4.691638
6.249999	4.615965
6.291666	4.555104
6.333332	4.499396
6.374999	4.500684
6.416666	4.442077
6.458332	4.383471
6.499999	4.310374
6.541666	4.251124
6.583332	4.190263

Continued on next column

Continued from previous column

Time	Voltage
6.624999	4.191229
6.666666	4.138097
6.708332	3.950685
6.749999	4.001563
6.791666	3.944889
6.833332	3.881775
6.874999	3.884673
6.916666	3.826066
6.958332	3.763274
6.999999	3.691143
7.041666	3.631571
7.083332	3.566846
7.124999	3.571354
7.166666	3.512104
7.208332	3.322761
7.249999	3.245478
7.291665	3.180109
7.333332	3.110877
7.374999	3.053236
7.416665	3.053558
7.458332	2.989478
7.499999	2.896417
7.541665	2.840386

Continued on next column

Continued from previous column

Time	Voltage
7.583332	2.782746
7.624999	2.728970
7.666665	2.728648
7.708332	2.678736
7.749999	2.606606
7.791665	2.537695
7.833332	2.472971
7.874999	2.411789
7.916665	2.412111
7.958332	2.359945
7.999999	2.284916
8.041665	2.233394
8.083332	2.289424
8.124999	2.227276
8.166665	2.228886
8.208332	2.169314
8.249999	2.091387
8.291665	2.026341
8.333332	1.966446
8.374999	1.903332
8.416665	1.905586
8.458332	1.845370
8.499999	1.767443

Continued on next column

Continued from previous column

Time	Voltage
8.541665	1.705939
8.583332	1.646367
8.624999	1.591303
8.666665	1.594201
8.708332	1.541713
8.749999	1.473447
8.791665	1.422569
8.833332	1.376522
8.874999	1.334016
8.916665	1.336914
8.958332	1.297951
8.999999	1.241599
9.041665	1.207788
9.083332	1.173011
9.124999	1.140165
9.166665	1.142098
9.208332	1.114405
9.249999	1.074475
9.291665	1.051290
9.333332	1.029394
9.374999	1.011683
9.416665	1.015547
9.458332	0.997837

Continued on next column

Continued from previous column

Time	Voltage
9.499998	0.968534
9.541665	0.959517
9.583332	0.946637
9.624998	0.938909
9.666665	0.936010
9.708332	0.933434
9.749998	0.915080
9.791665	0.912182
9.833332	0.909928
9.874998	0.908962
9.916665	0.913792
9.958332	0.916046
9.999998	0.905419
10.041665	0.907352
10.083332	0.910894
10.124998	0.917334
10.166665	0.923130
10.208332	0.925706
10.249998	0.913470
10.291665	0.921198
10.333332	0.922808
10.374998	0.929892
10.416665	0.932790

Continued on next column

Continued from previous column

Time	Voltage
10.458332	0.934400
10.499998	0.924740
10.541665	0.926994
10.583332	0.928926
10.624998	0.932468
10.666665	0.934722
10.708332	0.935688
10.749998	0.922808
10.791665	0.924096
10.833332	0.924418
10.874998	0.925384
10.916665	0.927638
10.958332	0.930214
10.999998	0.916368
11.041665	0.914114
11.083332	0.914758
11.124998	0.914436
11.166665	0.912182
11.208332	0.916368
11.249998	0.902199
11.291665	0.898979
11.333332	0.897047
11.374998	0.897691

Continued on next column

Continued from previous column

Time	Voltage
11.416665	0.898013
11.458331	0.903809
11.499998	0.887387
11.541665	0.884811
11.583331	0.885455
11.624998	0.886099
11.666665	0.885133
11.708331	0.889963
11.749998	0.873862
11.791665	0.872896
11.833331	0.874184
11.874998	0.875472
11.916665	0.876116
11.958331	0.880947
11.999998	0.865168
12.041665	0.866778
12.083331	0.869354
12.124998	0.869032
12.166665	0.870642
12.208331	0.875794
12.249998	0.862592
12.291665	0.864524
12.333331	0.867422

Continued on next column

Continued from previous column

Time	Voltage
12.374998	0.869354
12.416665	0.871930
12.458331	0.876438
12.499998	0.863880
12.541665	0.864202
12.583331	0.868710
12.624998	0.867422
12.666665	0.872252
12.708331	0.875794
12.749998	0.861304
12.791665	0.865168
12.833331	0.867100
12.874998	0.867422
12.916665	0.872252
12.958331	0.875472
12.999998	0.862270
13.041665	0.863880
13.083331	0.866134
13.124998	0.868388
13.166665	0.872252
13.208331	0.875472
13.249998	0.863880
13.291665	0.864202

Continued on next column

Continued from previous column

Time	Voltage
13.333331	0.867422
13.374998	0.867100
13.416665	0.872252
13.458331	0.875794
13.499998	0.862592
13.541664	0.864846
13.583331	0.865812
13.624998	0.869676
13.666664	0.871608
13.708331	0.875794
13.749998	0.862592
13.791664	0.863880
13.833331	0.866134
13.874998	0.869676
13.916664	0.871930
13.958331	0.875794
13.999998	0.862592
14.041664	0.863880
14.083331	0.866778
14.124998	0.870320
14.166664	0.872252
14.208331	0.877082
14.249998	0.863236

Continued on next column

Continued from previous column

Time	Voltage
14.291664	0.863558
14.333331	0.866134
14.374998	0.869676
14.416664	0.872574
14.458331	0.876438
14.499998	0.862914
14.541664	0.864202
14.583331	0.866456
14.624998	0.866778
14.666664	0.871608
14.708331	0.876760
14.749998	0.863236
14.791664	0.864202
14.833331	0.866456
14.874998	0.869354
14.916664	0.871608
14.958331	0.877082
14.999998	0.863558

Table A.8. Position Sensor Data for 1300 RPM.

Time	Voltage
0.000000	9.765007
0.041667	9.761786
0.083333	9.756634
0.125000	9.762108
0.166667	9.737313
0.208333	9.730872
0.250000	9.719924
0.291667	9.712195
0.333333	9.704145
0.375000	9.709941
0.416667	9.681603
0.458333	9.669367
0.500000	9.656164
0.541667	9.641995
0.583333	9.628792
0.625000	9.635555
0.666667	9.601421
0.708333	9.583709
0.750000	9.569541
0.791667	9.547965
0.833333	9.532186

Continued on next column

Continued from previous column

Time	Voltage
0.875000	9.539915
0.916667	9.498696
0.958333	9.476799
1.000000	9.460054
1.041667	9.437835
1.083333	9.419480
1.125000	9.428496
1.166666	9.381803
1.208333	9.356686
1.250000	9.333500
1.291666	9.312569
1.333333	9.285520
1.375000	9.293248
1.416666	9.246233
1.458333	9.214997
1.500000	9.181829
1.541666	9.153814
1.583333	9.132239
1.625000	9.142221
1.666666	9.085224
1.708333	9.051734
1.750000	9.015668
1.791666	8.986686

Continued on next column

Continued from previous column

Time	Voltage
1.833333	8.949976
1.875000	8.907147
1.916666	8.906181
1.958333	8.869149
2.000000	8.833083
2.041666	8.791865
2.083333	8.761273
2.125000	8.707496
2.166666	8.711682
2.208333	8.667888
2.250000	8.628280
2.291666	8.589637
2.333333	8.551639
2.375000	8.494642
2.416666	8.495286
2.458333	8.456000
2.500000	8.413494
2.541666	8.371309
2.583333	8.329447
2.625000	8.274060
2.666666	8.274060
2.708333	8.229943
2.750000	8.184217

Continued on next column

Continued from previous column

Time	Voltage
2.791666	8.142033
2.833333	8.096950
2.875000	8.037377
2.916666	8.039309
2.958333	7.992617
3.000000	7.945602
3.041666	7.899876
3.083333	7.852861
3.124999	7.788780
3.166666	7.789746
3.208333	7.741765
3.249999	7.692175
3.291666	7.641296
3.333333	7.594282
3.374999	7.529556
3.416666	7.530200
3.458333	7.477390
3.499999	7.427477
3.541666	7.375310
3.583333	7.322822
3.624999	7.255842
3.666666	7.255842
3.708333	7.205286

Continued on next column

Continued from previous column

Time	Voltage
3.749999	7.147323
3.791666	7.099020
3.833333	7.043956
3.874999	6.976976
3.916666	6.977620
3.958333	6.922556
3.999999	6.869745
4.041666	6.812104
4.083333	6.757039
4.124999	6.687484
4.166666	6.690060
4.208333	6.632419
4.249999	6.432770
4.291666	6.391552
4.333333	6.316200
4.374999	6.261458
4.416666	6.183530
4.458333	6.187394
4.499999	6.128787
4.541666	6.069215
4.583333	6.008998
4.624999	5.938155
4.666666	5.877616

Continued on next column

Continued from previous column

Time	Voltage
4.708333	5.881802
4.749999	5.816111
4.791666	5.756216
4.833333	5.701152
4.874999	5.623868
4.916666	5.561076
4.958333	5.564940
4.999999	5.505689
5.041666	5.444184
5.083333	5.388476
5.124999	5.312159
5.166666	5.262890
5.208333	5.263212
5.249999	5.206216
5.291666	5.162100
5.333332	5.208792
5.374999	5.128288
5.416666	5.068072
5.458332	5.071292
5.499999	5.005923
5.541666	4.944741
5.583332	4.882592
5.624999	4.804021

Continued on next column

Continued from previous column

Time	Voltage
5.666666	4.549308
5.708332	4.551240
5.749999	4.676181
5.791666	4.616931
5.833332	4.548664
5.874999	4.467194
5.916666	4.404080
5.958332	4.336457
5.999999	4.338067
6.041666	4.277529
6.083332	4.037951
6.124999	3.954228
6.166666	3.942313
6.208332	3.869216
6.249999	3.871470
6.291666	3.814474
6.333332	3.871470
6.374999	3.791933
6.416666	3.724632
6.458332	3.653790
6.499999	3.658298
6.541666	3.593895
6.583332	3.523375

Continued on next column

Continued from previous column

Time	Voltage
6.624999	3.316320
6.666666	3.246766
6.708332	3.140824
6.749999	3.105080
6.791666	3.102504
6.833332	3.004613
6.874999	2.931838
6.916666	2.861317
6.958332	2.801745
6.999999	2.748935
7.041666	2.741851
7.083332	2.692583
7.124999	2.609504
7.166666	2.534153
7.208332	2.462022
7.249999	2.412755
7.291665	2.393112
7.333332	2.335150
7.374999	2.260443
7.416665	2.310355
7.458332	2.243376
7.499999	2.208599
7.541665	2.176398

Continued on next column

Continued from previous column

Time	Voltage
7.583332	2.105877
7.624999	2.023764
7.666665	1.951312
7.708332	1.884012
7.749999	1.815101
7.791665	1.814779
7.833332	1.750055
7.874999	1.661824
7.916665	1.589371
7.958332	1.520139
7.999999	1.449618
8.041665	1.452194
8.083332	1.384250
8.124999	1.301171
8.166665	1.237413
8.208332	1.177841
8.249999	1.118591
8.291665	1.120845
8.333332	1.075441
8.374999	1.010395
8.416665	0.965636
8.458332	0.923774
8.499999	0.887709

Continued on next column

Continued from previous column

Time	Voltage
8.541665	0.852932
8.583332	0.860660
8.624999	0.813324
8.666665	0.783699
8.708332	0.758904
8.749999	0.740550
8.791665	0.724127
8.833332	0.727025
8.874999	0.696756
8.916665	0.684198
8.958332	0.684842
8.999999	0.690960
9.041665	0.697078
9.083332	0.700299
9.124999	0.687740
9.166665	0.699654
9.208332	0.711891
9.249999	0.717043
9.291665	0.724771
9.333332	0.727347
9.374999	0.718009
9.416665	0.727669
9.458332	0.737008

Continued on next column

Continued from previous column

Time	Voltage
9.499998	0.746024
9.541665	0.753430
9.583332	0.756328
9.624998	0.745702
9.666665	0.752464
9.708332	0.762125
9.749998	0.766311
9.791665	0.772429
9.833332	0.777903
9.874998	0.765345
9.916665	0.772429
9.958332	0.779513
9.999998	0.783699
10.041665	0.789818
10.083332	0.794648
10.124998	0.784021
10.166665	0.786275
10.208332	0.790784
10.249998	0.793038
10.291665	0.796580
10.333332	0.800122
10.374998	0.787563
10.416665	0.790462

Continued on next column

Continued from previous column

Time	Voltage
10.458332	0.793038
10.499998	0.794326
10.541665	0.796902
10.583332	0.801088
10.624998	0.787241
10.666665	0.788851
10.708332	0.788207
10.749998	0.789174
10.791665	0.791750
10.833332	0.795936
10.874998	0.779513
10.916665	0.780479
10.958332	0.781445
10.999998	0.784343
11.041665	0.786919
11.083332	0.789174
11.124998	0.774039
11.166665	0.776937
11.208332	0.778869
11.249998	0.779835
11.291665	0.782733
11.333332	0.789496
11.374998	0.775327

Continued on next column

Continued from previous column

Time	Voltage
11.416665	0.776615
11.458331	0.779513
11.499998	0.784665
11.541665	0.787241
11.583331	0.793038
11.624998	0.780157
11.666665	0.782411
11.708331	0.784343
11.749998	0.787563
11.791665	0.792394
11.833331	0.796580
11.874998	0.781767
11.916665	0.788529
11.958331	0.791428
11.999998	0.793682
12.041665	0.797546
12.083331	0.799800
12.124998	0.789496
12.166665	0.794648
12.208331	0.794326
12.249998	0.800444
12.291665	0.804308
12.333331	0.808816

Continued on next column

Continued from previous column

Time	Voltage
12.374998	0.796902
12.416665	0.801732
12.458331	0.805596
12.499998	0.812036
12.541665	0.815578
12.583331	0.821053
12.624998	0.809138
12.666665	0.816222
12.708331	0.820731
12.749998	0.825239
12.791665	0.829747
12.833331	0.838119
12.874998	0.828781
12.916665	0.835221
12.958331	0.839407
12.999998	0.849712
13.041665	0.851966
13.083331	0.861304
13.124998	0.855830
13.166665	0.862270
13.208331	0.871286
13.249998	0.879981
13.291665	0.882557

Continued on next column

Continued from previous column

Time	Voltage
13.333331	0.893827
13.374998	0.885133
13.416665	0.895759
13.458331	0.902521
13.499998	0.910572
13.541664	0.914758
13.583331	0.924740
13.624998	0.918300
13.666664	0.927316
13.708331	0.934400
13.749998	0.945671
13.791664	0.947281
13.833331	0.958551
13.874998	0.951789
13.916664	0.961449
13.958331	0.970466
13.999998	0.982380
14.041664	0.984956
14.083331	0.996549
14.124998	0.989142
14.166664	0.998481
14.208331	1.009107
14.249998	1.019089

Continued on next column

Continued from previous column

Time	Voltage
14.291664	1.020699
14.333331	1.034546
14.374998	1.025530
14.416664	1.036478
14.458331	1.047426
14.499998	1.057087
14.541664	1.059019
14.583331	1.068035
14.624998	1.063205
14.666664	1.071255
14.708331	1.083814
14.749998	1.091542
14.791664	1.093796
14.833331	1.103778
14.874998	1.096050
14.916664	1.101846
14.958331	1.113117
14.999998	1.122133

Table A.9. Position Sensor Data for 1400 RPM.

Time	Voltage
0.000000	9.740211
0.041667	9.733127
0.083333	9.723788
0.125000	9.712517
0.166667	9.701247
0.208333	9.689010
0.250000	9.679027
0.291667	9.662282
0.333333	9.651334
0.375000	9.639419
0.416667	9.623318
0.458333	9.608827
0.500000	9.589506
0.541667	9.575015
0.583333	9.553118
0.625000	9.538627
0.666667	9.519306
0.708333	9.495476
0.750000	9.471003
0.791667	9.448139
0.833333	9.428818

Continued on next column

Continued from previous column

Time	Voltage
0.875000	9.416259
0.916667	9.385023
0.958333	9.358296
1.000000	9.332534
1.041667	9.306129
1.083333	9.274893
1.125000	9.262334
1.166666	9.230454
1.208333	9.200507
1.250000	9.166051
1.291666	9.133205
1.333333	9.100359
1.375000	9.087478
1.416666	9.049158
1.458333	9.012770
1.500000	8.977670
1.541666	8.939993
1.583333	8.906181
1.625000	8.851760
1.666666	8.854336
1.708333	8.811186
1.750000	8.769968
1.791666	8.730359

Continued on next column

Continued from previous column

Time	Voltage
1.833333	8.688819
1.875000	8.629568
1.916666	8.631500
1.958333	8.587705
2.000000	8.543589
2.041666	8.503337
2.083333	8.456322
2.125000	8.395139
2.166666	8.394817
2.208333	8.347158
2.250000	8.303041
2.291666	8.252807
2.333333	8.203216
2.375000	8.140101
2.416666	8.140745
2.458333	8.089866
2.500000	8.039309
2.541666	7.988752
2.583333	7.936908
2.625000	7.876046
2.666666	7.872826
2.708333	7.820015
2.750000	7.765917

Continued on next column

Continued from previous column

Time	Voltage
2.791666	7.712462
2.833333	7.657719
2.875000	7.586231
2.916666	7.588807
2.958333	7.535353
3.000000	7.478678
3.041666	7.421037
3.083333	7.369514
3.124999	7.292552
3.166666	7.294806
3.208333	7.235877
3.249999	7.177270
3.291666	7.117053
3.333333	7.059412
3.374999	6.985993
3.416666	6.988247
3.458333	6.926420
3.499999	6.865237
3.541666	6.806630
3.583333	6.747701
3.624999	6.666553
3.666666	6.605692
3.708333	6.606980

Continued on next column

Continued from previous column

Time	Voltage
3.749999	6.545153
3.791666	6.483648
3.833333	6.421177
3.874999	6.340995
3.916666	6.278846
3.958333	6.278846
3.999999	6.215087
4.041666	6.012218
4.083333	5.940087
4.124999	5.858295
4.166666	5.797756
4.208333	5.798078
4.249999	5.730133
4.291666	5.659934
4.333333	5.593277
4.374999	5.515672
4.416666	5.441286
4.458333	5.439032
4.499999	5.377205
4.541666	5.308938
4.583333	5.242925
4.624999	5.163710
4.666666	5.098663

Continued on next column

Continued from previous column

Time	Voltage
4.708333	5.099629
4.749999	5.033616
4.791666	4.978552
4.833333	5.031362
4.874999	4.948927
4.916666	4.873576
4.958333	4.877118
4.999999	4.811749
5.041666	4.738008
5.083333	4.669419
5.124999	4.583763
5.166666	4.508734
5.208333	4.513886
5.249999	4.442721
5.291666	4.370268
5.333332	4.302324
5.374999	4.214736
5.416666	3.959058
5.458332	3.944567
5.499999	3.947465
5.541666	3.868250
5.583332	3.787747
5.624999	3.841523

Continued on next column

Continued from previous column

Time	Voltage
5.666666	3.766172
5.708332	3.696617
5.749999	3.694685
5.791666	3.622876
5.833332	3.554932
5.874999	3.462836
5.916666	3.256426
5.958332	3.145976
5.999999	3.146942
6.041666	3.108945
6.083332	3.008477
6.124999	2.913161
6.166666	2.847793
6.208332	2.787576
6.249999	2.786288
6.291666	2.724784
6.333332	2.662958
6.374999	2.571828
6.416666	2.494868
6.458332	2.421127
6.499999	2.419517
6.541666	2.356725
6.583332	2.289102

Continued on next column

Continued from previous column

Time	Voltage
6.624999	2.326777
6.666666	2.255291
6.708332	2.180262
6.749999	2.105877
6.791666	2.112962
6.833332	2.038899
6.874999	1.950024
6.916666	1.879503
6.958332	1.804153
6.999999	1.732344
7.041666	1.735564
7.083332	1.662790
7.124999	1.577457
7.166666	1.507258
7.208332	1.438670
7.249999	1.376200
7.291665	1.382318
7.333332	1.322746
7.374999	1.250615
7.416665	1.202314
7.458332	1.150470
7.499999	1.107320
7.541665	1.107964

Continued on next column

Continued from previous column

Time	Voltage
7.583332	1.068679
7.624999	1.013293
7.666665	0.976584
7.708332	0.944383
7.749999	0.916046
7.791665	0.918622
7.833332	0.895759
7.874999	0.858406
7.916665	0.840695
7.958332	0.824917
7.999999	0.818477
8.041665	0.822341
8.083332	0.816222
8.124999	0.796258
8.166665	0.795936
8.208332	0.795936
8.249999	0.804630
8.291665	0.804308
8.333332	0.810748
8.374999	0.799800
8.416665	0.804308
8.458332	0.811392
8.499999	0.816544

Continued on next column

Continued from previous column

Time	Voltage
8.541665	0.818799
8.583332	0.829103
8.624999	0.816222
8.666665	0.821375
8.708332	0.828137
8.749999	0.834577
8.791665	0.837797
8.833332	0.846491
8.874999	0.835221
8.916665	0.840051
8.958332	0.847779
8.999999	0.854864
9.041665	0.858084
9.083332	0.866456
9.124999	0.855508
9.166665	0.859694
9.208332	0.865490
9.249999	0.872252
9.291665	0.874184
9.333332	0.882235
9.374999	0.867100
9.416665	0.872252
9.458332	0.874506

Continued on next column

Continued from previous column

Time	Voltage
9.499998	0.876438
9.541665	0.879659
9.583332	0.885455
9.624998	0.869998
9.666665	0.869354
9.708332	0.874184
9.749998	0.874184
9.791665	0.878371
9.833332	0.881591
9.874998	0.866778
9.916665	0.867422
9.958332	0.869676
9.999998	0.869032
10.041665	0.873540
10.083332	0.878049
10.124998	0.860016
10.166665	0.865812
10.208332	0.862270
10.249998	0.862592
10.291665	0.866134
10.333332	0.869676
10.374998	0.853576
10.416665	0.854864

Continued on next column

Continued from previous column

Time	Voltage
10.458332	0.854864
10.499998	0.858406
10.541665	0.861948
10.583332	0.864846
10.624998	0.848746
10.666665	0.851000
10.708332	0.852610
10.749998	0.855186
10.791665	0.860660
10.833332	0.862592
10.874998	0.848746
10.916665	0.850356
10.958332	0.851644
10.999998	0.855186
11.041665	0.858084
11.083332	0.863880
11.124998	0.848424
11.166665	0.850356
11.208332	0.854864
11.249998	0.856474
11.291665	0.858406
11.333332	0.864202
11.374998	0.849390

Continued on next column

Continued from previous column

Time	Voltage
11.416665	0.850678
11.458331	0.852610
11.499998	0.856152
11.541665	0.858728
11.583331	0.863558
11.624998	0.848746
11.666665	0.851644
11.708331	0.853254
11.749998	0.856474
11.791665	0.861304
11.833331	0.867100
11.874998	0.853254
11.916665	0.852932
11.958331	0.854542
11.999998	0.858406
12.041665	0.862270
12.083331	0.865812
12.124998	0.852288
12.166665	0.854864
12.208331	0.859694
12.249998	0.862592
12.291665	0.866456
12.333331	0.935044

Continued on next column

Continued from previous column

Time	Voltage
12.374998	0.855508
12.416665	0.860982
12.458331	0.863236
12.499998	0.865168
12.541665	0.868066
12.583331	0.858406
12.624998	0.859050
12.666665	0.860338
12.708331	0.862592
12.749998	0.865812
12.791665	0.869032
12.833331	0.856474
12.874998	0.857762
12.916665	0.860016
12.958331	0.862592
12.999998	0.865168
13.041665	0.869998
13.083331	0.858728
13.124998	0.857440
13.166665	0.861304
13.208331	0.862592
13.249998	0.864202
13.291665	0.869676

Continued on next column

Continued from previous column

Time	Voltage
13.333331	0.856796
13.374998	0.857762
13.416665	0.861304
13.458331	0.862592
13.499998	0.866134
13.541664	0.869676
13.583331	0.856796
13.624998	0.858406
13.666664	0.861626
13.708331	0.861948
13.749998	0.865812
13.791664	0.869676
13.833331	0.856474
13.874998	0.858084
13.916664	0.860982
13.958331	0.862270
13.999998	0.866456
14.041664	0.869998
14.083331	0.856474
14.124998	0.858728
14.166664	0.860338
14.208331	0.863236
14.249998	0.866456

Continued on next column

Continued from previous column

Time	Voltage
14.291664	0.868710
14.333331	0.855508
14.374998	0.858728
14.416664	0.860982
14.458331	0.863236
14.499998	0.865812
14.541664	0.869998
14.583331	0.856152
14.624998	0.859372
14.666664	0.863558
14.708331	0.867744
14.749998	0.869676
14.791664	0.870642
14.833331	0.861948
14.874998	0.866134
14.916664	0.870964
14.958331	0.878371
14.999998	0.886743

Table A.10. Position Sensor Data for 1500 RPM.

Time	Voltage
0.000000	9.787548
0.041667	9.783040
0.083333	9.770481
0.125000	9.761464
0.166667	9.748584
0.208333	9.739567
0.250000	9.734415
0.291667	9.717026
0.333333	9.705111
0.375000	9.691908
0.416667	9.676129
0.458333	9.656808
0.500000	9.643283
0.541667	9.622996
0.583333	9.613013
0.625000	9.594336
0.666667	9.569219
0.708333	9.547965
0.750000	9.526712
0.791667	9.502883
0.833333	9.489680

Continued on next column

Continued from previous column

Time	Voltage
0.875000	9.462952
0.916667	9.435903
0.958333	9.406921
1.000000	9.382125
1.041667	9.351533
1.083333	9.337687
1.125000	9.306129
1.166666	9.270063
1.208333	9.240115
1.250000	9.202761
1.291666	9.168949
1.333333	9.158000
1.375000	9.118070
1.416666	9.082004
1.458333	9.039497
1.500000	9.001499
1.541666	8.961569
1.583333	8.903605
1.625000	8.905859
1.666666	8.865607
1.708333	8.821813
1.750000	8.776730
1.791666	8.734868

Continued on next column

Continued from previous column

Time	Voltage
1.833333	8.672074
1.875000	8.673362
1.916666	8.623771
1.958333	8.579011
2.000000	8.528132
2.041666	8.482083
2.083333	8.413494
2.125000	8.414460
2.166666	8.364225
2.208333	8.311414
2.250000	8.261823
2.291666	8.209978
2.333333	8.139457
2.375000	8.140423
2.416666	8.083426
2.458333	8.030293
2.500000	7.973296
2.541666	7.920485
2.583333	7.845133
2.625000	7.845455
2.666666	7.787814
2.708333	7.728563
2.750000	7.671566

Continued on next column

Continued from previous column

Time	Voltage
2.791666	7.612959
2.833333	7.535997
2.875000	7.536319
2.916666	7.476746
2.958333	7.417172
3.000000	7.350515
3.041666	7.290620
3.083333	7.211404
3.124999	7.213658
3.166666	7.149255
3.208333	7.083564
3.249999	7.019804
3.291666	6.955723
3.333333	6.876185
3.374999	6.878117
3.416666	6.809528
3.458333	6.741583
3.499999	6.675247
3.541666	6.608590
3.583333	6.387366
3.624999	6.321030
3.666666	6.321675
3.708333	6.244069

Continued on next column

Continued from previous column

Time	Voltage
3.749999	6.176768
3.791666	6.098518
3.833333	6.014472
3.874999	5.944595
3.916666	5.944595
3.958333	5.867311
3.999999	5.799044
4.041666	5.725625
4.083333	5.639003
4.124999	5.566550
4.166666	5.565906
4.208333	5.494419
4.249999	5.419711
4.291666	5.349512
4.333333	5.263212
4.374999	5.189793
4.416666	5.192369
4.458333	5.119272
4.499999	5.046819
4.541666	4.982094
4.583333	5.020736
4.624999	4.939266
4.666666	4.941842

Continued on next column

Continued from previous column

Time	Voltage
4.708333	4.868423
4.749999	4.788886
4.791666	4.719653
4.833333	4.625947
4.874999	4.542868
4.916666	4.549308
4.958333	4.470093
4.999999	4.389589
5.041666	4.316814
5.083333	4.218600
5.124999	3.961634
5.166666	4.064678
5.208333	4.066932
5.249999	3.985141
5.291666	3.908502
5.333332	3.813186
5.374999	3.732039
5.416666	3.655078
5.458332	3.653468
5.499999	3.573608
5.541666	3.499224
5.583332	3.264154
5.624999	3.179787

Continued on next column

Continued from previous column

Time	Voltage
5.666666	3.103470
5.708332	3.102504
5.749999	3.014595
5.791666	2.915093
5.833332	2.826862
5.874999	2.750867
5.916666	2.819456
5.958332	2.818812
5.999999	2.609504
6.041666	2.527391
6.083332	2.421771
6.124999	2.345454
6.166666	2.268493
6.208332	2.272035
6.249999	2.316151
6.291666	2.233716
6.333332	2.133892
6.374999	2.053712
6.416666	1.969345
6.458332	1.886910
6.499999	1.892706
6.541666	1.808983
6.583332	1.708837

Continued on next column

Continued from previous column

Time	Voltage
6.624999	1.633165
6.666666	1.558780
6.708332	1.487938
6.749999	1.492446
6.791666	1.430298
6.833332	1.355913
6.874999	1.302137
6.916666	1.252547
6.958332	1.211652
6.999999	1.213906
7.041666	1.172045
7.083332	1.116981
7.124999	1.083814
7.166666	1.052900
7.208332	1.022631
7.249999	1.026174
7.291665	0.999125
7.333332	0.961127
7.374999	0.937299
7.416665	0.917334
7.458332	0.901555
7.499999	0.904775
7.541665	0.890929

Continued on next column

Continued from previous column

Time	Voltage
7.583332	0.861626
7.624999	0.847135
7.666665	0.837797
7.708332	0.829747
7.749999	0.830713
7.791665	0.827815
7.833332	0.808494
7.874999	0.801410
7.916665	0.800122
7.958332	0.798834
7.999999	0.802054
8.041665	0.803342
8.083332	0.790462
8.124999	0.791428
8.166665	0.796258
8.208332	0.802376
8.249999	0.803664
8.291665	0.811714
8.333332	0.799478
8.374999	0.800766
8.416665	0.806562
8.458332	0.812036
8.499999	0.814290

Continued on next column

Continued from previous column

Time	Voltage
8.541665	0.823307
8.583332	0.806562
8.624999	0.808494
8.666665	0.814290
8.708332	0.816544
8.749999	0.818799
8.791665	0.821375
8.833332	0.806884
8.874999	0.805596
8.916665	0.809460
8.958332	0.809782
8.999999	0.812358
9.041665	0.813002
9.083332	0.796258
9.124999	0.794326
9.166665	0.796580
9.208332	0.795936
9.249999	0.800122
9.291665	0.798190
9.333332	0.780157
9.374999	0.783377
9.416665	0.778869
9.458332	0.779513

Continued on next column

Continued from previous column

Time	Voltage
9.499998	0.784665
9.541665	0.784987
9.583332	0.765023
9.624998	0.764057
9.666665	0.764379
9.708332	0.761481
9.749998	0.765667
9.791665	0.766311
9.833332	0.748600
9.874998	0.748278
9.916665	0.748278
9.958332	0.750854
9.999998	0.751820
10.041665	0.756328
10.083332	0.738618
10.124998	0.742482
10.166665	0.739906
10.208332	0.743770
10.249998	0.746346
10.291665	0.750532
10.333332	0.736686
10.374998	0.739906
10.416665	0.742482

Continued on next column

Continued from previous column

Time	Voltage
10.458332	0.746346
10.499998	0.749888
10.541665	0.753752
10.583332	0.739262
10.624998	0.742804
10.666665	0.745058
10.708332	0.745380
10.749998	0.748922
10.791665	0.756328
10.833332	0.742160
10.874998	0.743126
10.916665	0.743770
10.958332	0.750210
10.999998	0.751498
11.041665	0.758582
11.083332	0.743770
11.124998	0.744736
11.166665	0.749244
11.208332	0.753430
11.249998	0.756328
11.291665	0.762447
11.333332	0.746346
11.374998	0.747634

Continued on next column

Continued from previous column

Time	Voltage
11.416665	0.750532
11.458331	0.752786
11.499998	0.756650
11.541665	0.760837
11.583331	0.745380
11.624998	0.745702
11.666665	0.750210
11.708331	0.755684
11.749998	0.756972
11.791665	0.763091
11.833331	0.749888
11.874998	0.747634
11.916665	0.752142
11.958331	0.756006
11.999998	0.758260
12.041665	0.765345
12.083331	0.748600
12.124998	0.749888
12.166665	0.753752
12.208331	0.756006
12.249998	0.759871
12.291665	0.764701
12.333331	0.748600

Continued on next column

Continued from previous column

Time	Voltage
12.374998	0.751176
12.416665	0.752786
12.458331	0.757616
12.499998	0.760837
12.541665	0.766633
12.583331	0.751498
12.624998	0.755362
12.666665	0.761803
12.708331	0.762769
12.749998	0.767599
12.791665	0.774683
12.833331	0.762125
12.874998	0.765667
12.916665	0.771141
12.958331	0.775971
12.999998	0.779191
13.041665	0.828459
13.083331	0.772751
13.124998	0.779835
13.166665	0.784665
13.208331	0.789174
13.249998	0.794004
13.291665	0.786597

Continued on next column

Continued from previous column

Time	Voltage
13.333331	0.790462
13.374998	0.797868
13.416665	0.801732
13.458331	0.809460
13.499998	0.813646
13.541664	0.804952
13.583331	0.812036
13.624998	0.816866
13.666664	0.822985
13.708331	0.832645
13.749998	0.835221
13.791664	0.830391
13.833331	0.836831
13.874998	0.842627
13.916664	0.852288
13.958331	0.863558
13.999998	0.867422
14.041664	0.861304
14.083331	0.869354
14.124998	0.877727
14.166664	0.886099
14.208331	0.898013
14.249998	0.900911

Continued on next column

Continued from previous column

Time	Voltage
14.291664	0.898335
14.333331	0.907674
14.374998	0.915080
14.416664	0.928282
14.458331	0.939553
14.499998	0.941807
14.541664	0.939231
14.583331	0.951145
14.624998	0.961449
14.666664	0.972398
14.708331	0.975940
14.749998	0.987854
14.791664	0.985922
14.833331	0.995583
14.874998	1.005887
14.916664	1.019411
14.958331	1.019733
14.999998	1.034546

Table A.11. Position Sensor Data for 1600 RPM.

Time	Voltage
0.000000	9.806547
0.041667	9.794310
0.083333	9.794632
0.125000	9.797853
0.166667	9.803649
0.208333	9.804615
0.250000	9.801395
0.291667	9.788192
0.333333	9.786260
0.375000	9.780785
0.416667	9.774345
0.458333	9.769193
0.500000	9.761142
0.541667	9.750516
0.583333	9.743431
0.625000	9.734093
0.666667	9.723144
0.708333	9.711551
0.750000	9.700281
0.791667	9.686756
0.833333	9.672265

Continued on next column

Continued from previous column

Time	Voltage
0.875000	9.659706
0.916667	9.640063
0.958333	9.623640
1.000000	9.606573
1.041667	9.590150
1.083333	9.570185
1.125000	9.553118
1.166666	9.526712
1.208333	9.508035
1.250000	9.481629
1.291666	9.469393
1.333333	9.443309
1.375000	9.414327
1.416666	9.387922
1.458333	9.361516
1.500000	9.331890
1.541666	9.317399
1.583333	9.289384
1.625000	9.257182
1.666666	9.222404
1.708333	9.186338
1.750000	9.157034
1.791666	9.142865

Continued on next column

Continued from previous column

Time	Voltage
1.833333	9.104223
1.875000	9.066869
1.916666	9.027582
1.958333	8.989906
2.000000	8.948366
2.041666	8.891047
2.083333	8.891691
2.125000	8.848862
2.166666	8.803458
2.208333	8.760307
2.250000	8.715869
2.291666	8.655329
2.333333	8.657261
2.375000	8.607348
2.416666	8.559368
2.458333	8.508811
2.500000	8.460508
2.541666	8.393850
2.583333	8.395461
2.625000	8.343938
2.666666	8.290805
2.708333	8.238316
2.750000	8.183895

Continued on next column

Continued from previous column

Time	Voltage
2.791666	8.115949
2.833333	8.116271
2.875000	8.060884
2.916666	8.004853
2.958333	7.947212
3.000000	7.889571
3.041666	7.816151
3.083333	7.815185
3.124999	7.752714
3.166666	7.695073
3.208333	7.632602
3.249999	7.571096
3.291666	7.491236
3.333333	7.493168
3.374999	7.429731
3.416666	7.367260
3.458333	7.304145
3.499999	7.236199
3.541666	7.157305
3.583333	7.159559
3.624999	7.088394
3.666666	7.020770
3.708333	6.954757

Continued on next column

Continued from previous column

Time	Voltage
3.749999	6.886168
3.791666	6.801478
3.833333	6.804054
3.874999	6.731278
3.916666	6.663333
3.958333	6.592167
3.999999	6.519070
4.041666	6.434702
4.083333	6.359994
4.124999	6.360316
4.166666	6.288185
4.208333	6.215087
4.249999	6.002558
4.291666	5.909495
4.333333	5.827382
4.374999	5.830280
4.416666	5.752996
4.458333	5.677323
4.499999	5.603903
4.541666	5.509553
4.583333	5.430016
4.624999	5.431948
4.666666	5.362071

Continued on next column

Continued from previous column

Time	Voltage
4.708333	5.280601
4.749999	5.198166
4.791666	5.108968
4.833333	5.032650
4.874999	5.036515
4.916666	4.950859
4.958333	5.009143
4.999999	4.933148
5.041666	4.837510
5.083333	4.753786
5.124999	4.756041
5.166666	4.673283
5.208333	4.592458
5.249999	4.510988
5.291666	4.408266
5.333332	4.329051
5.374999	4.065966
5.416666	4.066932
5.458332	3.983853
5.499999	4.083033
5.541666	3.976446
5.583332	3.893367
5.624999	3.811576

Continued on next column

Continued from previous column

Time	Voltage
5.666666	3.809966
5.708332	3.726887
5.749999	3.641231
5.791666	3.538831
5.833332	3.455430
5.874999	3.231631
5.916666	3.233563
5.958332	3.147586
5.999999	3.059999
6.041666	2.935702
6.083332	2.849403
6.124999	2.769222
6.166666	2.770832
6.208332	2.695481
6.249999	2.615300
6.291666	2.506138
6.333332	2.415975
6.374999	2.329998
6.416666	2.333862
6.458332	2.254647
6.499999	2.288458
6.541666	2.187024
6.583332	2.097827

Continued on next column

Continued from previous column

Time	Voltage
6.624999	2.005410
6.666666	1.919755
6.708332	1.922653
6.749999	1.833456
6.791666	1.736208
6.833332	1.656349
6.874999	1.582931
6.916666	1.516275
6.958332	1.519173
6.999999	1.458635
7.041666	1.390690
7.083332	1.341100
7.124999	1.291189
7.166666	1.251581
7.208332	1.251903
7.249999	1.211008
7.291665	1.156910
7.333332	1.120201
7.374999	1.084780
7.416665	1.051934
7.458332	1.054511
7.499999	1.026818
7.541665	0.979482

Continued on next column

Continued from previous column

Time	Voltage
7.583332	0.949213
7.624999	0.921198
7.666665	0.891895
7.708332	0.894149
7.749999	0.869998
7.791665	0.829425
7.833332	0.803020
7.874999	0.784343
7.916665	0.765667
7.958332	0.767921
7.999999	0.754718
8.041665	0.725415
8.083332	0.714789
8.124999	0.708671
8.166665	0.705451
8.208332	0.706739
8.249999	0.708993
8.291665	0.691926
8.333332	0.696434
8.374999	0.703519
8.416665	0.708671
8.458332	0.711891
8.499999	0.720907

Continued on next column

Continued from previous column

Time	Voltage
8.541665	0.712213
8.583332	0.721229
8.624999	0.728313
8.666665	0.735398
8.708332	0.738296
8.749999	0.747956
8.791665	0.739262
8.833332	0.743448
8.874999	0.749888
8.916665	0.755362
8.958332	0.758904
8.999999	0.765989
9.041665	0.754396
9.083332	0.758582
9.124999	0.760515
9.166665	0.763091
9.208332	0.766311
9.249999	0.767599
9.291665	0.752786
9.333332	0.751176
9.374999	0.750854
9.416665	0.749244
9.458332	0.755040

Continued on next column

Continued from previous column

Time	Voltage
9.499998	0.753430
9.541665	0.734754
9.583332	0.728313
9.624998	0.726381
9.666665	0.721229
9.708332	0.725093
9.749998	0.722517
9.791665	0.699654
9.833332	0.697400
9.874998	0.694502
9.916665	0.694824
9.958332	0.699010
9.999998	0.699976
10.041665	0.686130
10.083332	0.689028
10.124998	0.694180
10.166665	0.697722
10.208332	0.701587
10.249998	0.709637
10.291665	0.694502
10.333332	0.695790
10.374998	0.699332
10.416665	0.702875

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Time	Voltage
10.458332	0.707383
10.499998	0.709959
10.541665	0.693536
10.583332	0.696434
10.624998	0.693858
10.666665	0.698366
10.708332	0.700299
10.749998	0.701265
10.791665	0.688706
10.833332	0.688706
10.874998	0.693214
10.916665	0.694502
10.958332	0.698366
10.999998	0.704163
11.041665	0.688384
11.083332	0.690960
11.124998	0.694502
11.166665	0.700299
11.208332	0.703197
11.249998	0.707061
11.291665	0.692248
11.333332	0.694502
11.374998	0.697400

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Time	Voltage
11.416665	0.698688
11.458331	0.702875
11.499998	0.707061
11.541665	0.690638
11.583331	0.692892
11.624998	0.695146
11.666665	0.697722
11.708331	0.701909
11.749998	0.706417
11.791665	0.690316
11.833331	0.692248
11.874998	0.695790
11.916665	0.698044
11.958331	0.700621
11.999998	0.706095
12.041665	0.689672
12.083331	0.692570
12.124998	0.694180
12.166665	0.697722
12.208331	0.701265
12.249998	0.707705
12.291665	0.690638
12.333331	0.692248

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Time	Voltage
12.374998	0.694502
12.416665	0.696756
12.458331	0.701265
12.499998	0.708027
12.541665	0.689672
12.583331	0.692892
12.624998	0.695468
12.666665	0.698688
12.708331	0.701265
12.749998	0.705451
12.791665	0.690638
12.833331	0.692892
12.874998	0.695146
12.916665	0.697078
12.958331	0.702231
12.999998	0.688706
13.041665	0.692892
13.083331	0.695468
13.124998	0.697400
13.166665	0.699010
13.208331	0.704163
13.249998	0.691604
13.291665	0.694824

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Continued from previous column

Time	Voltage
13.333331	0.694824
13.374998	0.696112
13.416665	0.698366
13.458331	0.703519
13.499998	0.690638
13.541664	0.693536
13.583331	0.695468
13.624998	0.699976
13.666664	0.700943
13.708331	0.700943
13.749998	0.691604
13.791664	0.693858
13.833331	0.695146
13.874998	0.696756
13.916664	0.700943
13.958331	0.704485
13.999998	0.692248
14.041664	0.693858
14.083331	0.695146
14.124998	0.697722
14.166664	0.700943
14.208331	0.703519
14.249998	0.691282

Continued on next column

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Time	Voltage
14.291664	0.690960
14.333331	0.697078
14.374998	0.698366
14.416664	0.701909
14.458331	0.703841
14.499998	0.692248
14.541664	0.694180
14.583331	0.695146
14.624998	0.698366
14.666664	0.700621
14.708331	0.704163
14.749998	0.692248
14.791664	0.693858
14.833331	0.693858
14.874998	0.698366
14.916664	0.700943
14.958331	0.704163
14.999998	0.691604

Table A.12. Position Sensor Data for 1700 RPM.

Time	Voltage
0.000000	9.871595
0.041667	9.857104
0.083333	9.838749
0.125000	9.826834
0.166667	9.807513
0.208333	9.788514
0.250000	9.769837
0.291667	9.747939
0.333333	9.729584
0.375000	9.717992
0.416667	9.686112
0.458333	9.669689
0.500000	9.640385
0.541667	9.613657
0.583333	9.588862
0.625000	9.575659
0.666667	9.547643
0.708333	9.516729
0.750000	9.482595
0.791667	9.452648
0.833333	9.421734

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Time	Voltage
0.875000	9.407887
0.916667	9.375685
0.958333	9.333500
1.000000	9.299366
1.041667	9.258792
1.083333	9.222726
1.125000	9.211455
1.166666	9.169271
1.208333	9.128374
1.250000	9.085868
1.291666	9.043039
1.333333	8.997313
1.375000	8.985398
1.416666	8.942569
1.458333	8.892013
1.500000	8.845642
1.541666	8.797983
1.583333	8.749358
1.625000	8.687209
1.666666	8.685277
1.708333	8.631822
1.750000	8.581909
1.791666	8.530064

Continued on next column

Continued from previous column

Time	Voltage
1.833333	8.477897
1.875000	8.408341
1.916666	8.407697
1.958333	8.349734
2.000000	8.296923
2.041666	8.237350
2.083333	8.184539
2.125000	8.107899
2.166666	8.107577
2.208333	8.049614
2.250000	7.989396
2.291666	7.929501
2.333333	7.867030
2.375000	7.790390
2.416666	7.792966
2.458333	7.729207
2.500000	7.666413
2.541666	7.599756
2.583333	7.535997
2.625000	7.455492
2.666666	7.456458
2.708333	7.390767
2.750000	7.323788

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Continued from previous column

Time	Voltage
2.791666	7.258418
2.833333	7.190795
2.875000	7.105783
2.916666	7.107393
2.958333	7.037837
3.000000	6.967638
3.041666	6.894218
3.083333	6.828205
3.124999	6.737396
3.166666	6.738363
3.208333	6.668163
3.249999	6.597642
3.291666	6.522934
3.333333	6.449193
3.374999	6.216376
3.416666	6.139092
3.458333	6.140380
3.499999	6.065351
3.541666	5.985491
3.583333	5.913682
3.624999	5.815145
3.666666	5.740438
3.708333	5.743336

Continued on next column

Continued from previous column

Time	Voltage
3.749999	5.660900
3.791666	5.584583
3.833333	5.505367
3.874999	5.414559
3.916666	5.337276
3.958333	5.338886
3.999999	5.258704
4.041666	5.180777
4.083333	5.103493
4.124999	5.145355
4.166666	5.065174
4.208333	5.066462
4.249999	4.984992
4.291666	4.906099
4.333333	4.822053
4.374999	4.723195
4.416666	4.643980
4.458333	4.642048
4.499999	4.558646
4.541666	4.476855
4.583333	4.392809
4.624999	4.291375
4.666666	4.209262

Continued on next column

Continued from previous column

Time	Voltage
4.708333	3.996411
4.749999	3.999631
4.791666	4.039561
4.833333	3.953584
4.874999	3.854726
4.916666	3.767782
4.958333	3.678907
4.999999	3.685025
5.041666	3.598403
5.083333	3.512104
5.124999	3.279933
5.166666	3.184295
5.208333	3.093166
5.249999	3.097996
5.291666	2.989156
5.333332	2.906077
5.374999	2.811083
5.416666	2.724462
5.458332	2.656518
5.499999	2.660382
5.541666	2.562812
5.583332	2.470717
5.624999	2.366385

Continued on next column

Continued from previous column

Time	Voltage
5.666666	2.283950
5.708332	2.324201
5.749999	2.327421
5.791666	2.238868
5.833332	2.154179
5.874999	2.053390
5.916666	1.973531
5.958332	1.899790
5.999999	1.829914
6.041666	1.832168
6.083332	1.770985
6.124999	1.694669
6.166666	1.638961
6.208332	1.587761
6.249999	1.540103
6.291666	1.540425
6.333332	1.498886
6.374999	1.437382
6.416666	1.395842
6.458332	1.357523
6.499999	1.318882
6.541666	1.319204
6.583332	1.287325

Continued on next column

Continued from previous column

Time	Voltage
6.624999	1.236125
6.666666	1.205212
6.708332	1.178163
6.749999	1.156266
6.791666	1.159164
6.833332	1.141454
6.874999	1.112151
6.916666	1.105710
6.958332	1.103134
6.999999	1.104100
7.041666	1.106676
7.083332	1.112473
7.124999	1.103134
7.166666	1.109252
7.208332	1.116981
7.249999	1.125997
7.291665	1.129539
7.333332	1.134691
7.374999	1.122777
7.416665	1.127285
7.458332	1.130827
7.499999	1.128573
7.541665	1.132115

Continued on next column

Continued from previous column

Time	Voltage
7.583332	1.136945
7.624999	1.119879
7.666665	1.119235
7.708332	1.117303
7.749999	1.115693
7.791665	1.118591
7.833332	1.119235
7.874999	1.102490
7.916665	1.102490
7.958332	1.104100
7.999999	1.107642
8.041665	1.111507
8.083332	1.112473
8.124999	1.101202
8.166665	1.105710
8.208332	1.106998
8.249999	1.112795
8.291665	1.117947
8.333332	1.121811
8.374999	1.113761
8.416665	1.119557
8.458332	1.123421
8.499999	1.132115

Continued on next column

Continued from previous column

Time	Voltage
8.541665	1.135979
8.583332	1.143386
8.624999	1.136301
8.666665	1.143386
8.708332	1.147250
8.749999	1.156910
8.791665	1.159808
8.833332	1.165282
8.874999	1.157554
8.916665	1.164316
8.958332	1.169468
8.999999	1.178163
9.041665	1.181061
9.083332	1.190721
9.124999	1.179451
9.166665	1.185569
9.208332	1.194263
9.249999	1.200704
9.291665	1.202636
9.333332	1.212940
9.374999	1.202314
9.416665	1.207466
9.458332	1.213584

Continued on next column

Continued from previous column

Time	Voltage
9.499998	1.219702
9.541665	1.224532
9.583332	1.231939
9.624998	1.219702
9.666665	1.226142
9.708332	1.233549
9.749998	1.236769
9.791665	1.239667
9.833332	1.248683
9.874998	1.235803
9.916665	1.240633
9.958332	1.249649
9.999998	1.255767
10.041665	1.259954
10.083332	1.270902
10.124998	1.258344
10.166665	1.262852
10.208332	1.270902
10.249998	1.277020
10.291665	1.281528
10.333332	1.290867
10.374998	1.278308
10.416665	1.288291

Continued on next column

Continued from previous column

Time	Voltage
10.458332	1.294731
10.499998	1.302137
10.541665	1.306645
10.583332	1.314373
10.624998	1.305035
10.666665	1.310187
10.708332	1.316628
10.749998	1.323712
10.791665	1.328220
10.833332	1.336914
10.874998	1.324678
10.916665	1.331762
10.958332	1.338202
10.999998	1.343355
11.041665	1.348185
11.083332	1.355913
11.124998	1.343677
11.166665	1.352049
11.208332	1.356879
11.249998	1.362997
11.291665	1.369115
11.333332	1.372336
11.374998	1.363641

Continued on next column

Continued from previous column

Time	Voltage
11.416665	1.368149
11.458331	1.372658
11.499998	1.379098
11.541665	1.381352
11.583331	1.387148
11.624998	1.376522
11.666665	1.379098
11.708331	1.381030
11.749998	1.388758
11.791665	1.390690
11.833331	1.394554
11.874998	1.379742
11.916665	1.381352
11.958331	1.387148
11.999998	1.392622
12.041665	1.393266
12.083331	1.397130
12.124998	1.383928
12.166665	1.386182
12.208331	1.386826
12.249998	1.389724
12.291665	1.393588
12.333331	1.398740

Continued on next column

Continued from previous column

Time	Voltage
12.374998	1.384572
12.416665	1.380064
12.458331	1.383606
12.499998	1.388436
12.541665	1.390690
12.583331	1.396164
12.624998	1.380708
12.666665	1.382318
12.708331	1.388758
12.749998	1.389080
12.791665	1.392622
12.833331	1.399062
12.874998	1.383284
12.916665	1.384250
12.958331	1.389080
12.999998	1.392622
13.041665	1.394876
13.083331	1.403249
13.124998	1.386182
13.166665	1.392300
13.208331	1.397774
13.249998	1.400995
13.291665	1.405825

Continued on next column

Continued from previous column

Time	Voltage
13.333331	1.414197
13.374998	1.397452
13.416665	1.402927
13.458331	1.409367
13.499998	1.409689
13.541664	1.415807
13.583331	1.407757
13.624998	1.410977
13.666664	1.417417
13.708331	1.421603
13.749998	1.425789
13.791664	1.430942
13.833331	1.421925
13.874998	1.427721
13.916664	1.431264
13.958331	1.435450
13.999998	1.439314
14.041664	1.448008
14.083331	1.437382
14.124998	1.443822
14.166664	1.449618
14.208331	1.454770
14.249998	1.459601

Continued on next column

Continued from previous column

Time	Voltage
14.291664	1.465397
14.333331	1.454126
14.374998	1.458957
14.416664	1.464109
14.458331	1.469905
14.499998	1.472481
14.541664	1.480209
14.583331	1.468617
14.624998	1.471515
14.666664	1.475379
14.708331	1.479243
14.749998	1.483429
14.791664	1.486972
14.833331	1.475701
14.874998	1.479243
14.916664	1.478921
14.958331	1.484395
14.999998	1.488260

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APPENDIX B:
REMUS Speed Calibration Results

This Appendix provides position vs time, speed vs time, and speed vs position plots for propeller RPMs between 600-1700 in 100 RPM increments. It also includes the averaging process done to estimate steady state vehicle speed corresponding to each propeller RPM. It also provides the approximate vehicle speed for tank positions of 1, 2, 3, 4, and 5 feet.

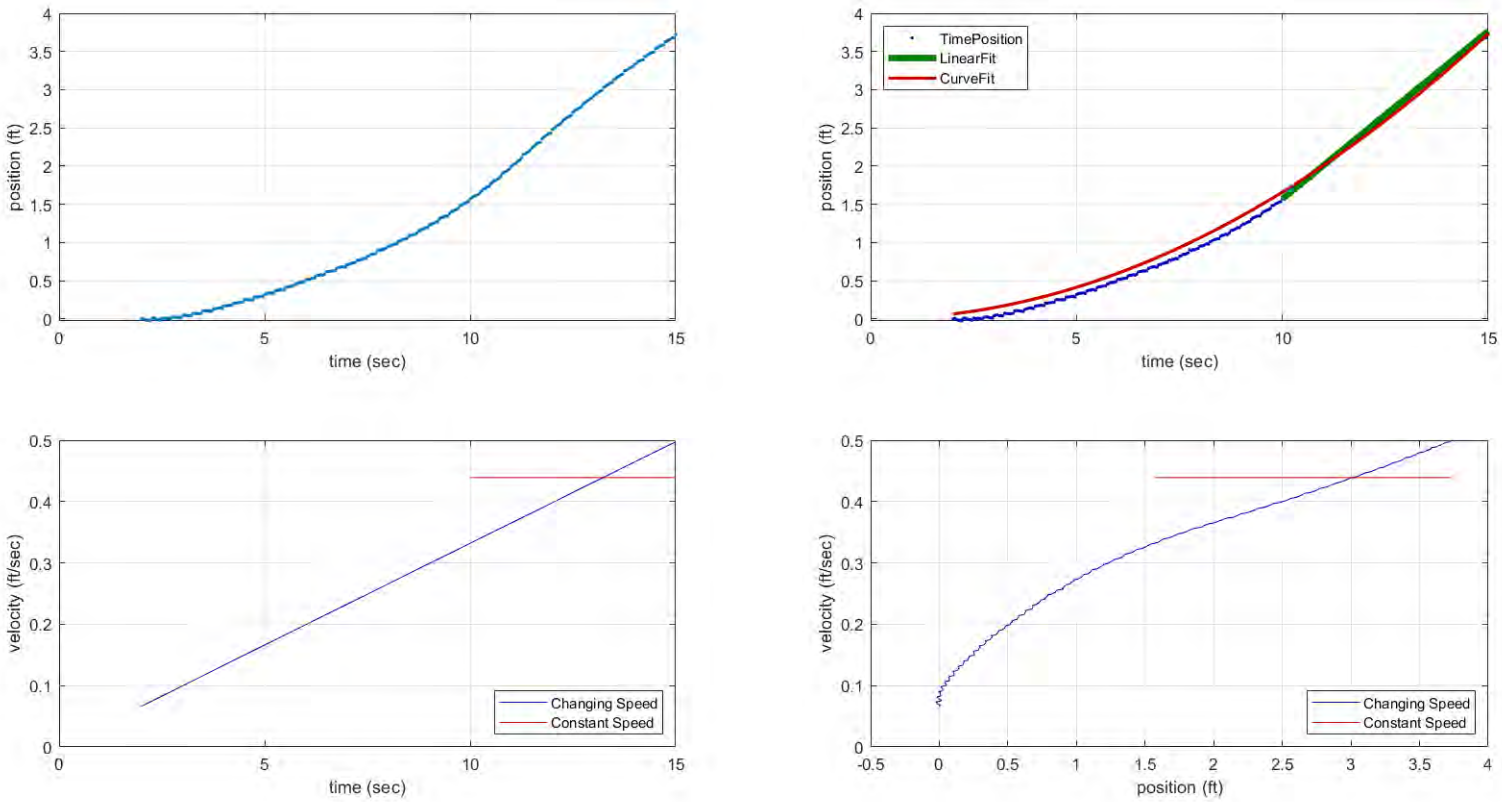

Figure B.1. Speed Calibration for 600RPM.

Table B.1. Vehicle Speed and Time Data Points Averaged to Find Steady State Vehicle Speed Corresponding to 600 RPM of the REMUS 100.

Time (s)	Vehicle Speed (ft/s)
15	0.4975
14	0.4645
13	0.4314

Table B.2. Vehicle Speed at Different Tank Positions for 600 RPM.

Position (ft)	Vehicle Speed (ft/s)
1	0.274
2	0.3652
3	0.439
4	0.464
5	0.464

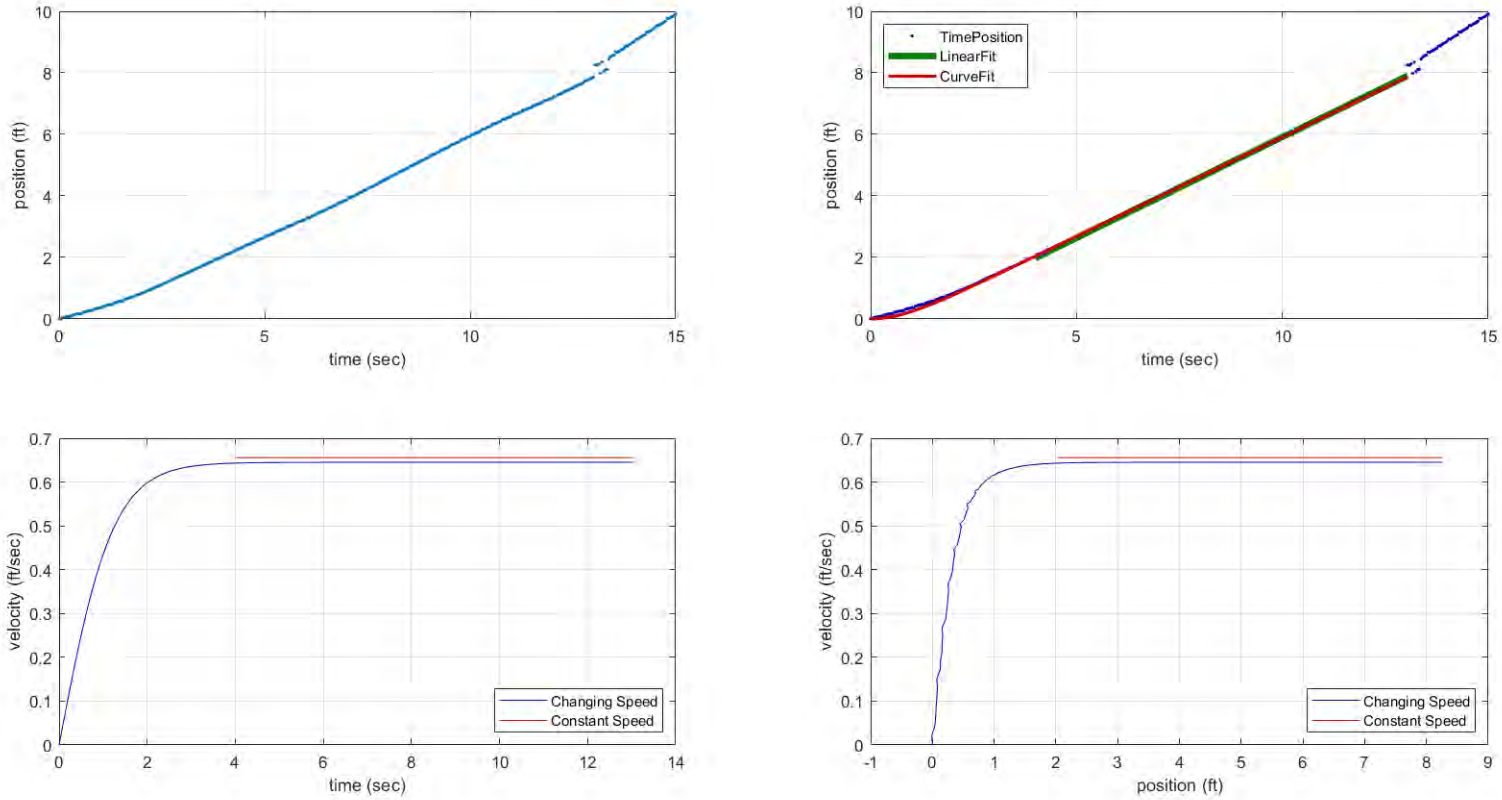

Figure B.2. Speed Calibration for 700RPM.

Table B.3. Vehicle Speed and Time Data Points Averaged to Find Steady State Vehicle Speed Corresponding to 700 RPM of the REMUS 100.

Time (s)	Vehicle Speed (ft/s)
15	0.6451
14	0.6451
13	0.6451

Table B.4. Vehicle Speed at Different Tank Positions for 700 RPM.

Position (ft)	Vehicle Speed (ft/s)
1	0.6174
2	0.6431
3	0.6449
4	0.6451
5	0.6451

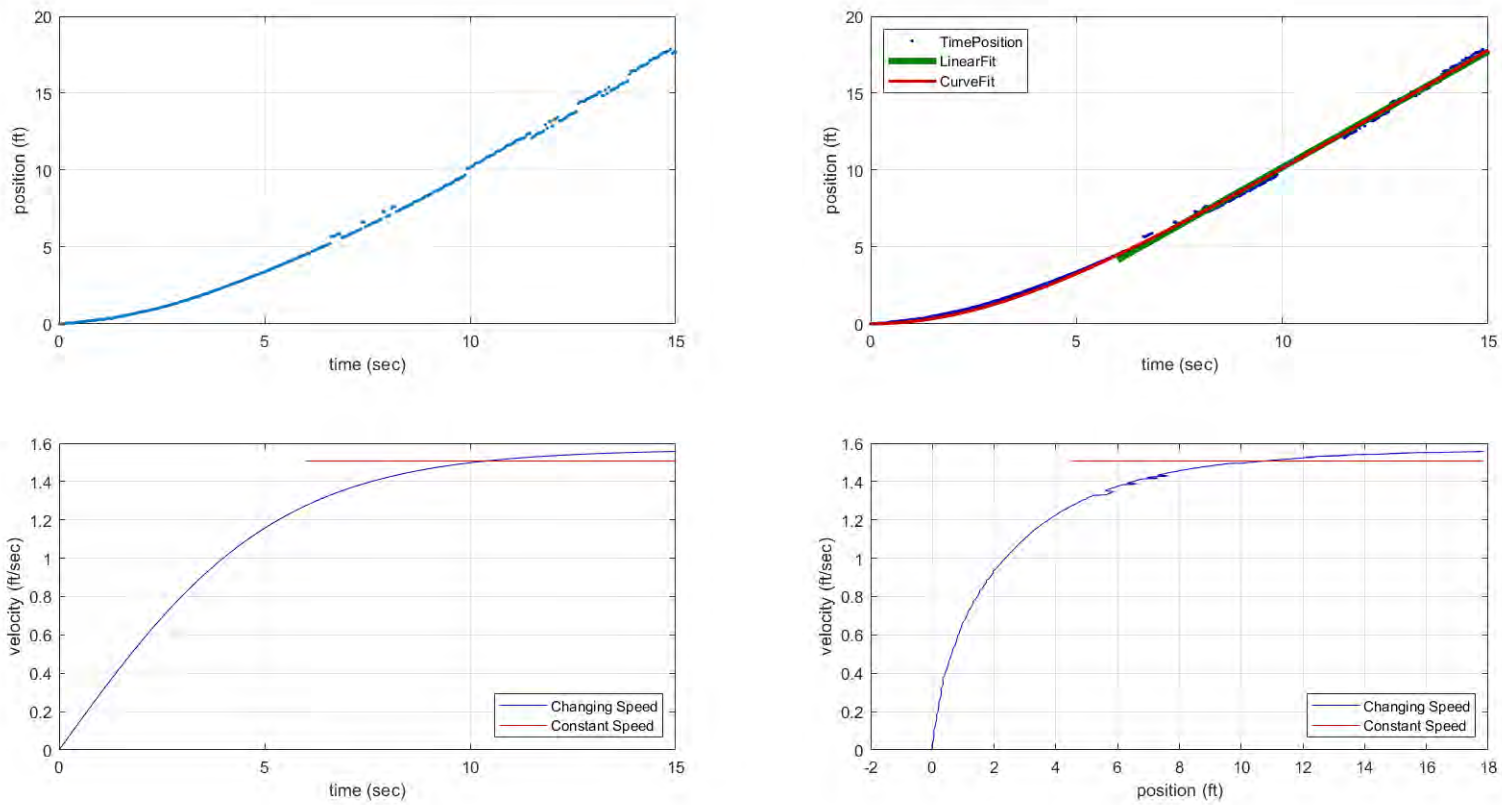

Figure B.3. Speed Calibration for 800RPM.

Table B.5. Vehicle Speed and Time Data Points Averaged to Find Steady State Vehicle Speed Corresponding to 800 RPM of the REMUS 100.

Time (s)	Vehicle Speed (ft/s)
15	1.557
14	1.552
13	1.545

Table B.6. Vehicle Speed at Different Tank Positions for 800 RPM.

Position (ft)	Vehicle Speed (ft/s)
1	0.6707
2	0.9412
3	1.11
4	1.225
5	1.314

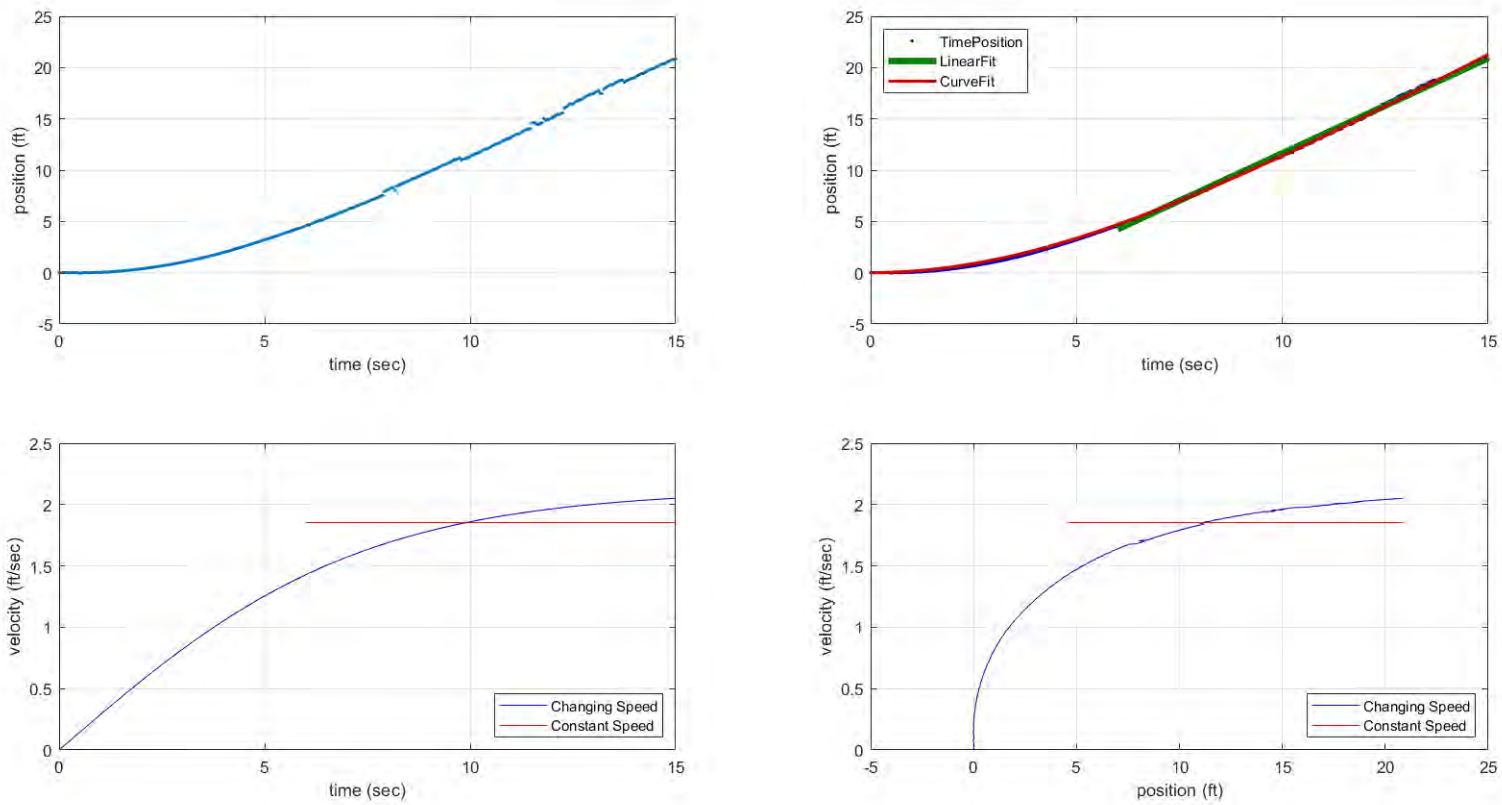

Figure B.4. Speed Calibration for 900RPM.

Table B.7. Vehicle Speed and Time Data Points Averaged to Find Steady State Vehicle Speed Corresponding to 900 RPM of the REMUS 100.

Time (s)	Vehicle Speed (ft/s)
15	2.052
14	2.03
13	2.002

Table B.8. Vehicle Speed at Different Tank Positions for 900 RPM.

Position (ft)	Vehicle Speed (ft/s)
1	0.8206
2	1.061
3	1.231
4	1.366
5	1.473

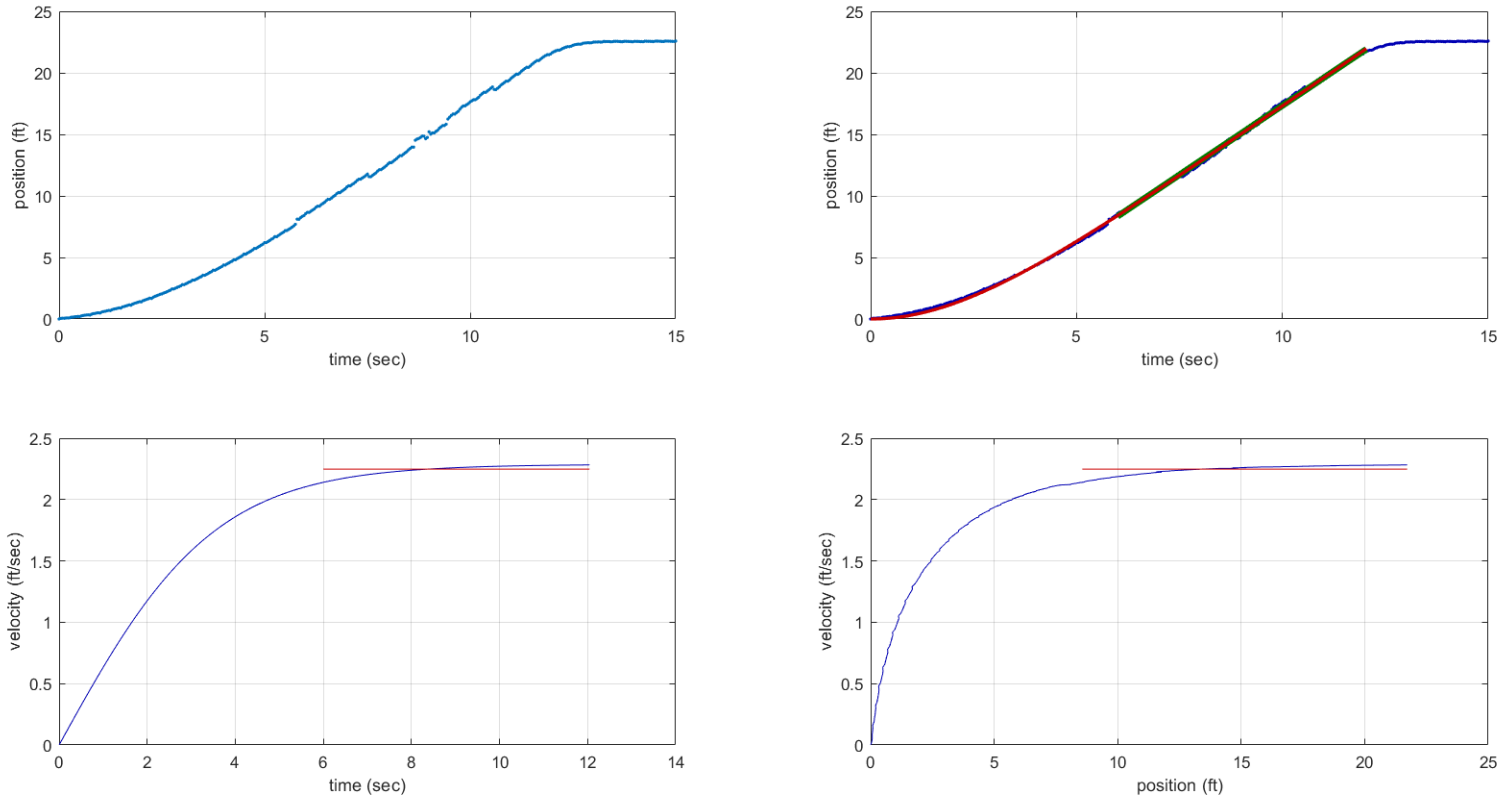

Figure B.5. Speed Calibration for 1000RPM.

Table B.9. Vehicle Speed and Time Data Points Averaged to Find Steady State Vehicle Speed Corresponding to 900 RPM of the REMUS 100.

Time (s)	Vehicle Speed (ft/s)
15	1.917
14	1.917
13	1.917

Table B.10. Vehicle Speed at Different Tank Positions for 1000 RPM.

Position (ft)	Vehicle Speed (ft/s)
1	1.22
2	1.579
3	1.737
4	1.819
5	1.86

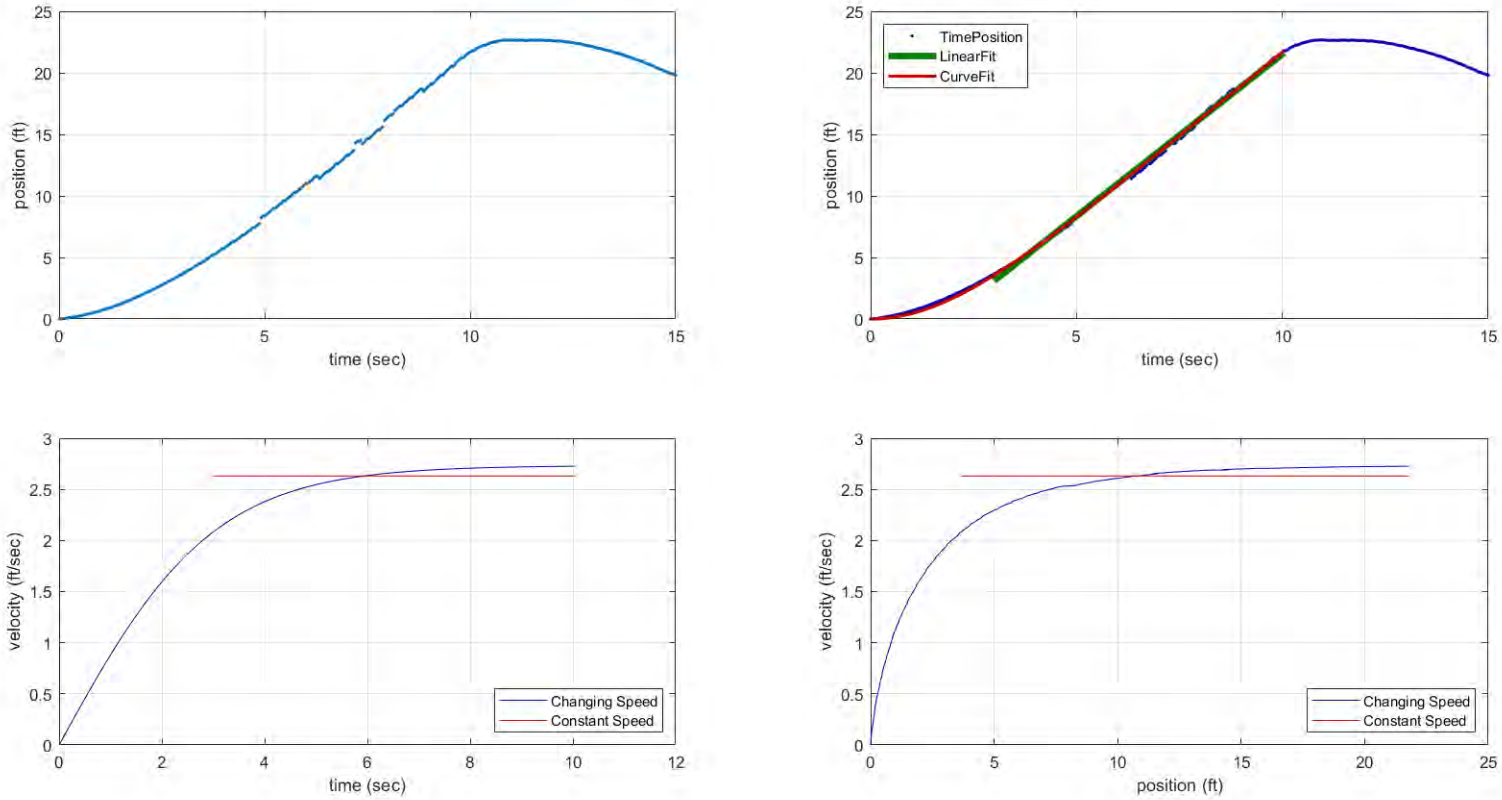

Figure B.6. Speed Calibration for 1100RPM.

Table B.11. Vehicle Speed and Time Data Points Averaged to Find Steady State Vehicle Speed Corresponding to 1100 RPM of the REMUS 100.

Time (s)	Vehicle Speed (ft/s)
10	2.726
9	2.72
8	2.707

Table B.12. Vehicle Speed at Different Tank Positions for 1100 RPM.

Position (ft)	Vehicle Speed (ft/s)
1	0.8461
2	1.62
3	1.926
4	2.145
5	2.298

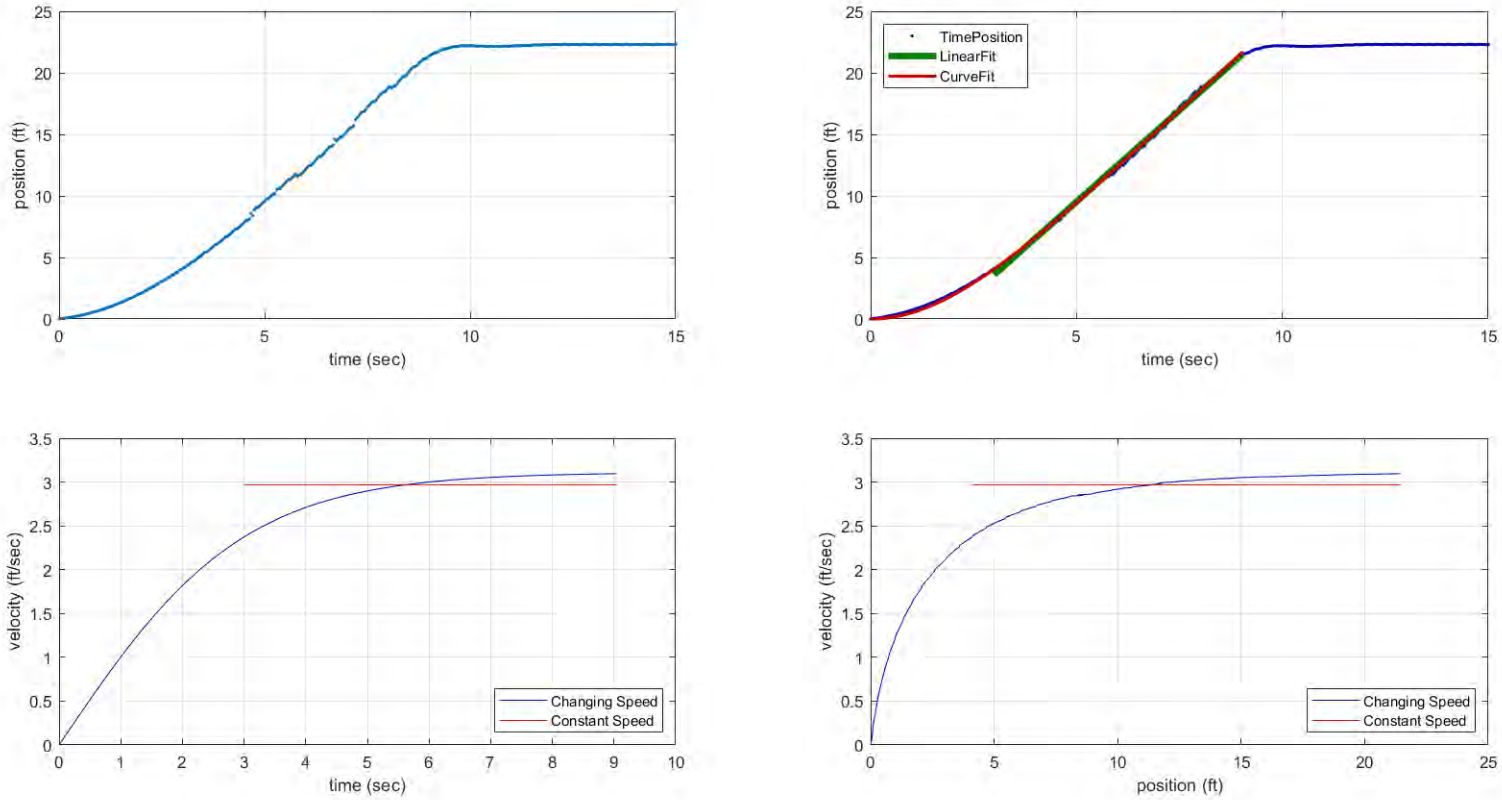

Figure B.7. Speed Calibration for 1200RPM.

Table B.13. Vehicle Speed and Time Data Points Averaged to Find Steady State Vehicle Speed Corresponding to 1200 RPM of the REMUS 100.

Time (s)	Vehicle Speed (ft/s)
8	3.095
7	3.081
6	3.053

Table B.14. Vehicle Speed at Different Tank Positions for 1200 RPM.

Position (ft)	Vehicle Speed (ft/s)
1	1.23
2	1.789
3	2.127
4	2.355
5	2.536

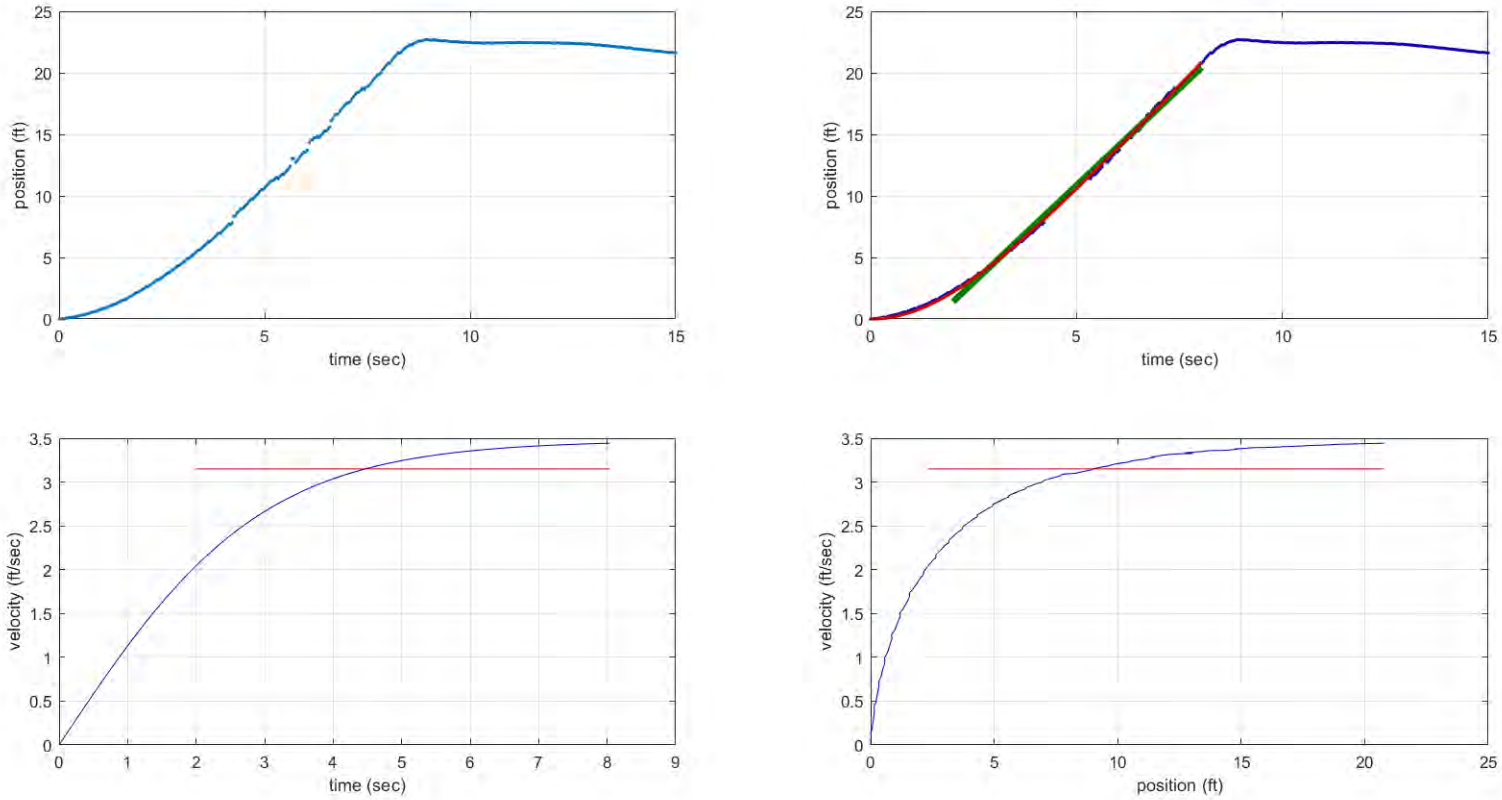

Figure B.8. Speed Calibration for 1300RPM.

Table B.15. Vehicle Speed and Time Data Points Averaged to Find Steady State Vehicle Speed Corresponding to 1300 RPM of the REMUS 100.

Time (s)	Vehicle Speed (ft/s)
8	3.443
7	3.413
6	3.355

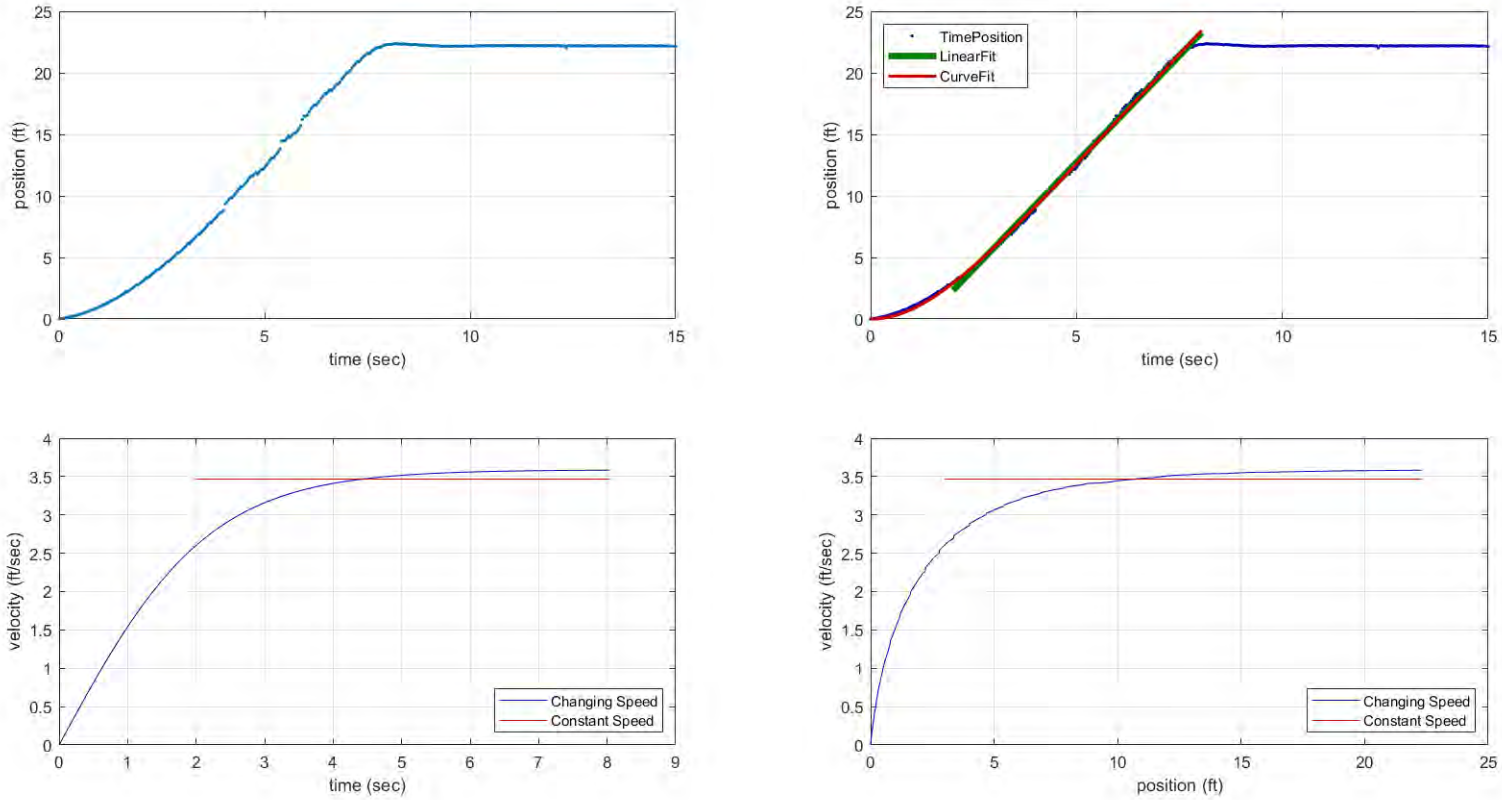

Figure B.9. Speed Calibration for 1400RPM.

Table B.16. Vehicle Speed and Time Data Points Averaged to Find Steady State Vehicle Speed Corresponding to 1400 RPM of the REMUS 100.

Time (s)	Vehicle Speed (ft/s)
8	3.584
7	3.577
6	3.56

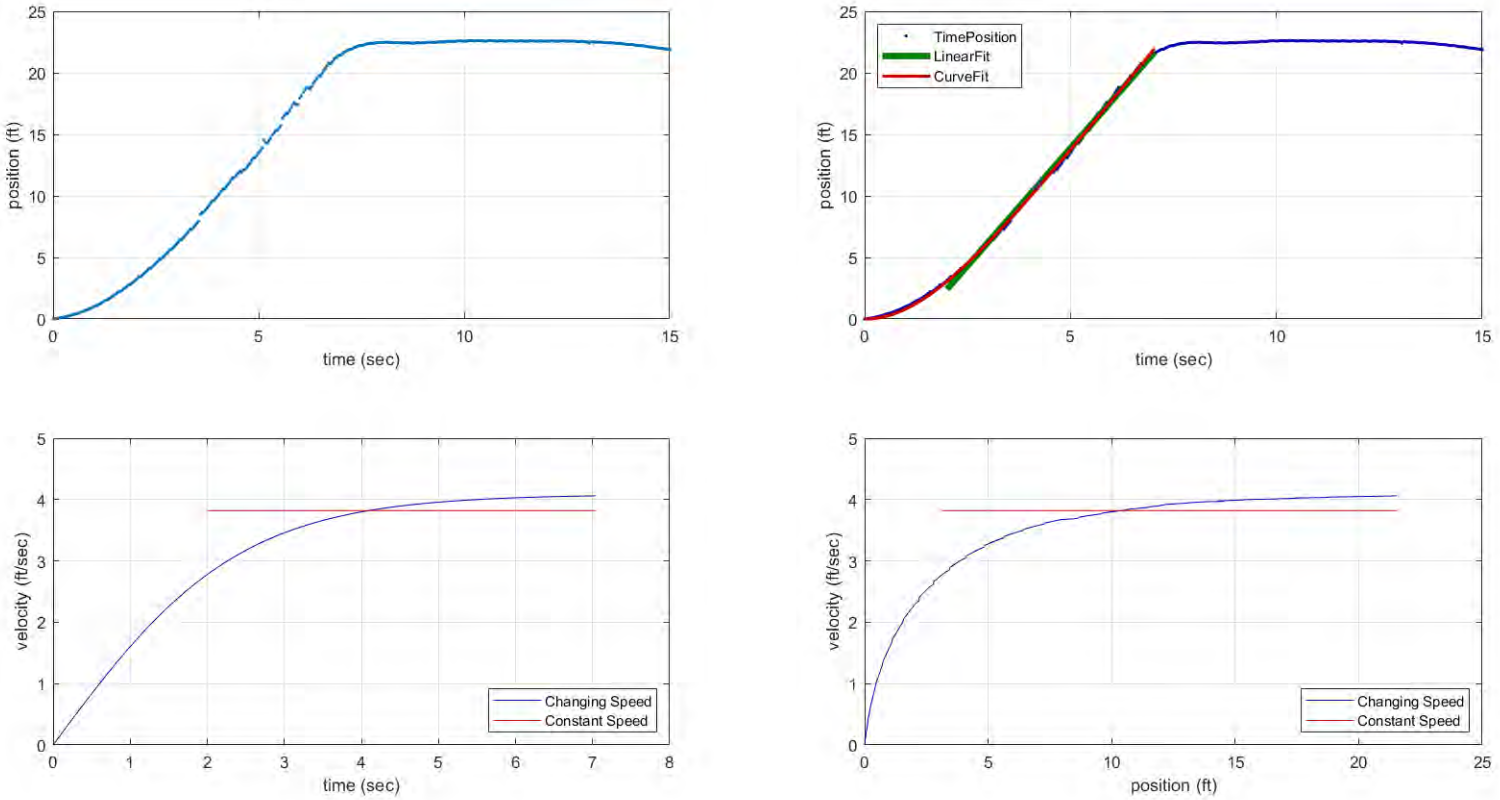

Figure B.10. Speed Calibration for 1500RPM.

Table B.17. Vehicle Speed and Time Data Points Averaged to Find Steady State Vehicle Speed Corresponding to 1500 RPM of the REMUS 100.

Time (s)	Vehicle Speed (ft/s)
7	4.06
6	4.029
5	3.958

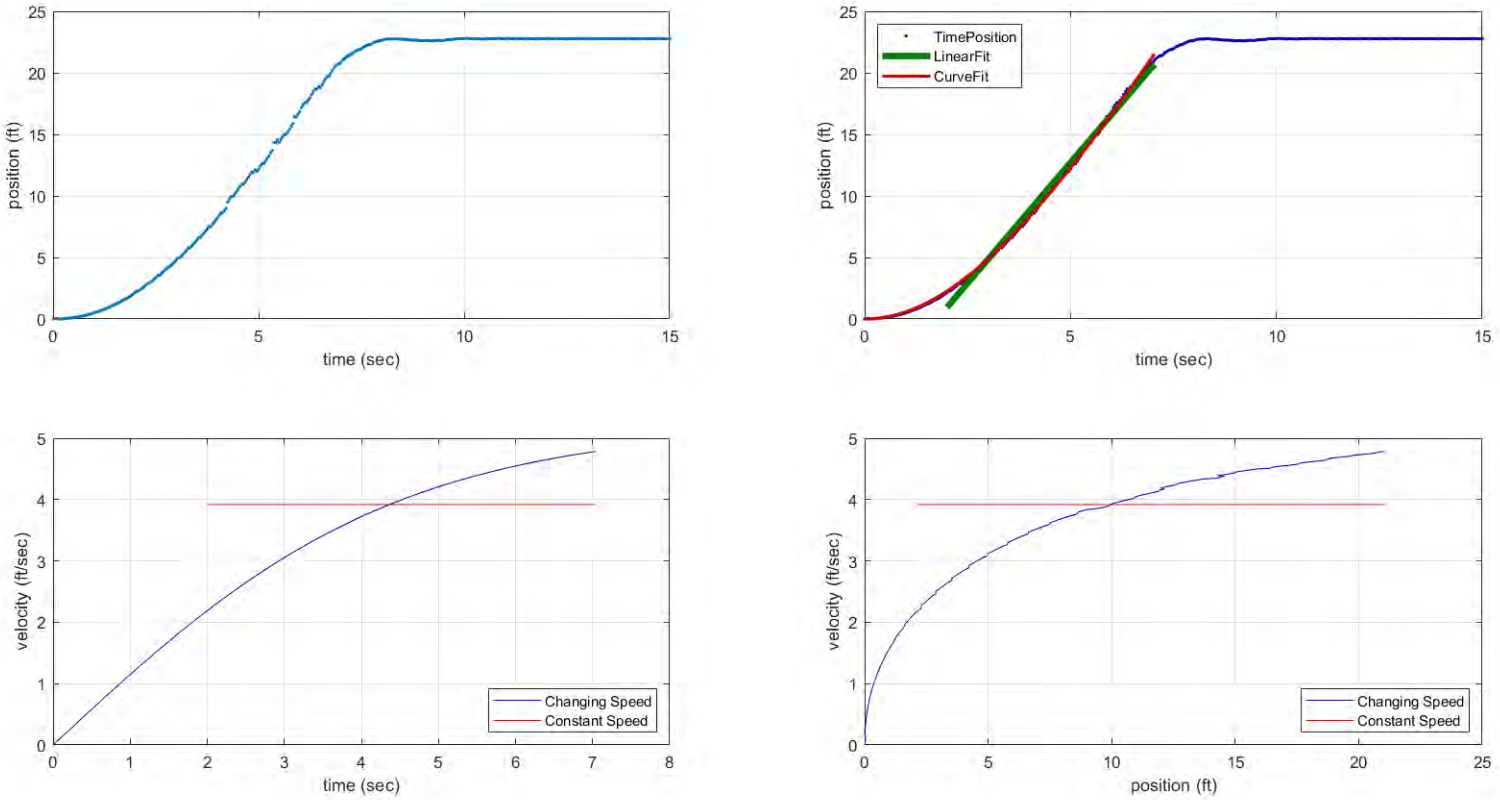

Figure B.11. Speed Calibration for 1600RPM.

Table B.18. Vehicle Speed and Time Data Points Averaged to Find Steady State Vehicle Speed Corresponding to 1600 RPM of the REMUS 100.

Time (s)	Vehicle Speed (ft/s)
7	4.777
6	4.547
5	4.208

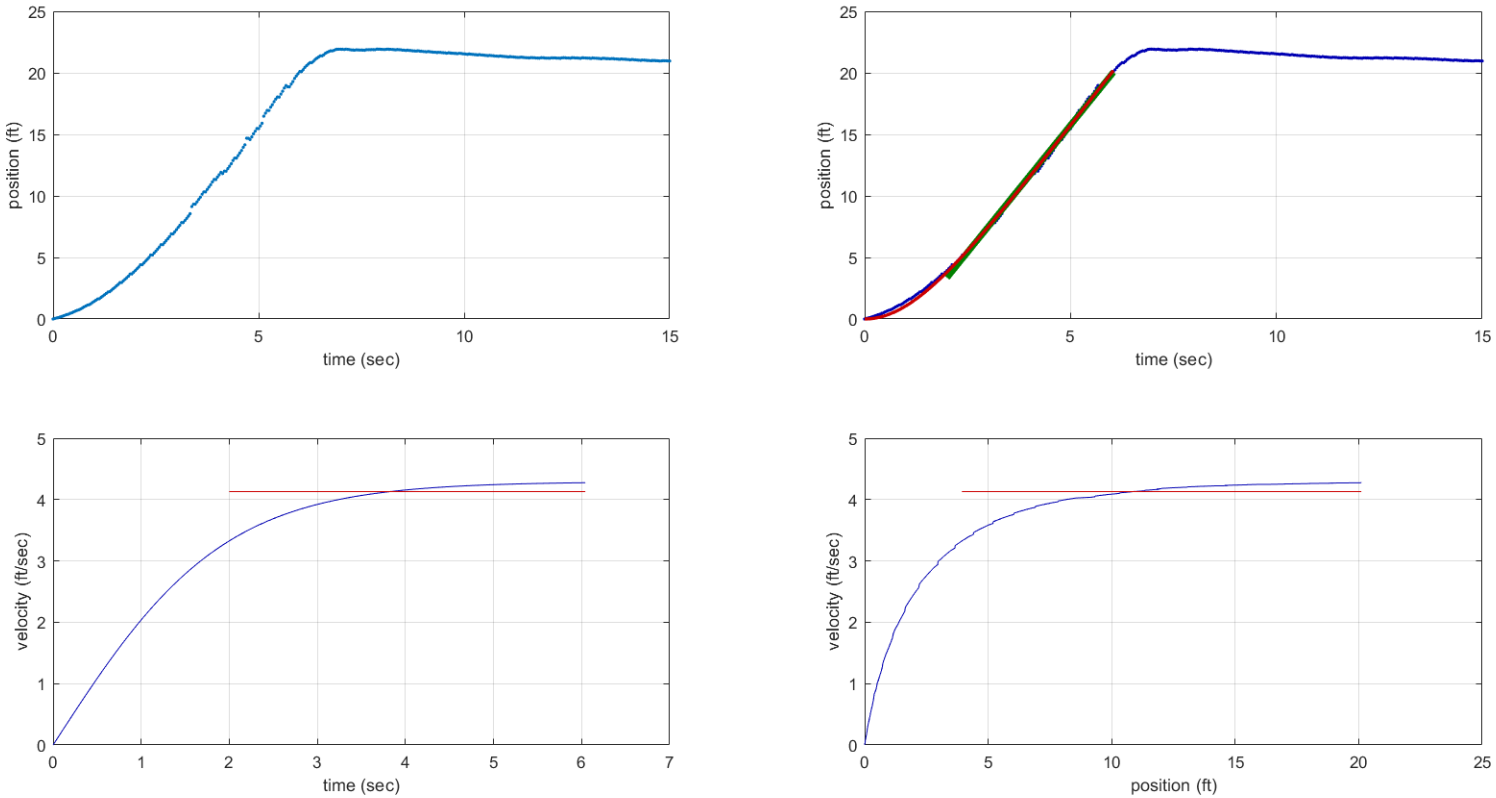

Figure B.12. Speed Calibration for 1700RPM.

Table B.19. Vehicle Speed and Time Data Points Averaged to Find Steady State Vehicle Speed Corresponding to 1700 RPM of the REMUS 100.

Time (s)	Vehicle Speed (ft/s)
6	4.274
5	4.243
4	4.156

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APPENDIX C:
Marine Vegetation Deflection Supplementary Pictures

Figure C.1. Synthetic Giant Kelp Deflection at 1 inch.

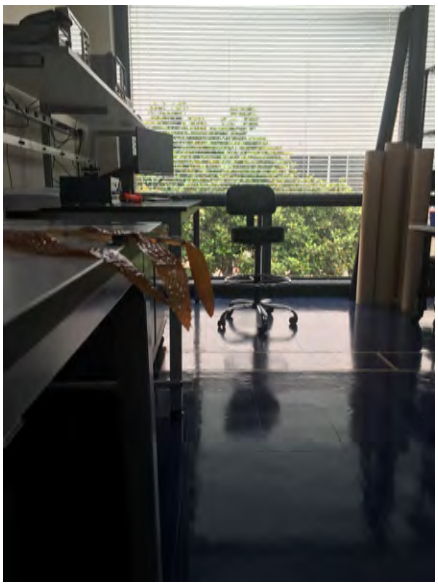

Figure C.2. Synthetic Giant Kelp Deflection at 2 inches.

Figure C.3. Synthetic Giant Kelp Deflection at 3 inches.

Figure C.4. Synthetic Giant Kelp Deflection at 4 inches.

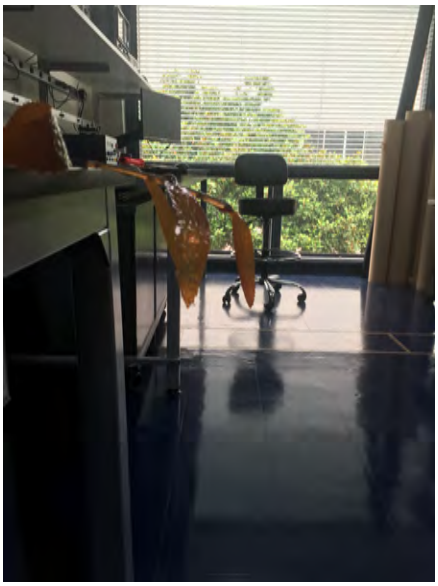

Figure C.5. Synthetic Giant Kelp Deflection at 5 inches.

Figure C.6. Synthetic Giant Kelp Deflection at 6 inches.

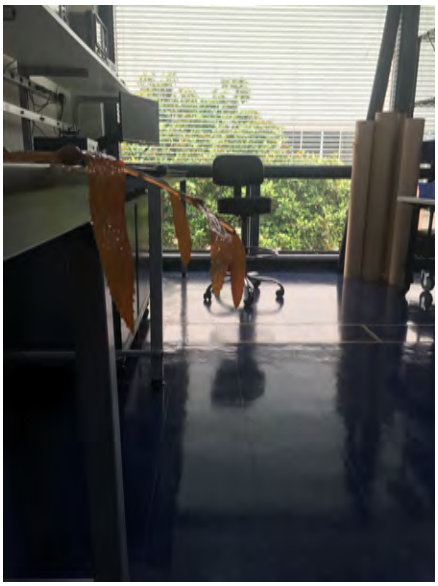

Figure C.7. Synthetic Giant Kelp Deflection at 7 inches.

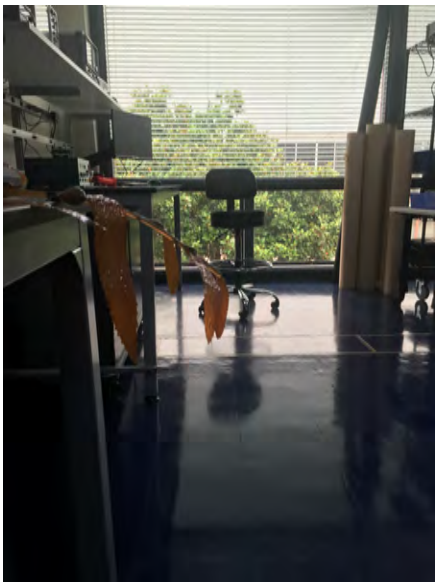

Figure C.8. Synthetic Giant Kelp Deflection at 8 inches.

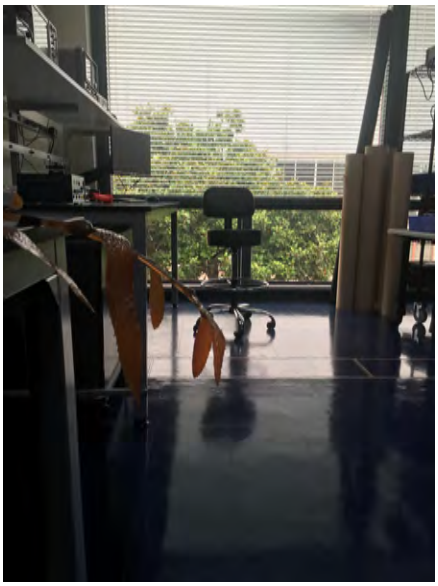

Figure C.9. Synthetic Giant Kelp Deflection at 9 inches.

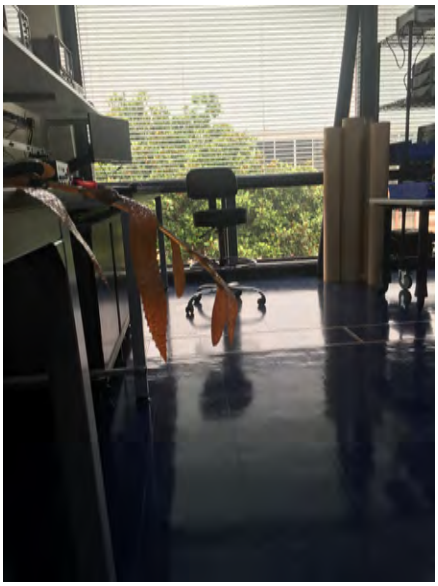

Figure C.10. Synthetic Giant Kelp Deflection at 10 inches.

Figure C.11. Synthetic Giant Kelp Deflection at 11 inches.

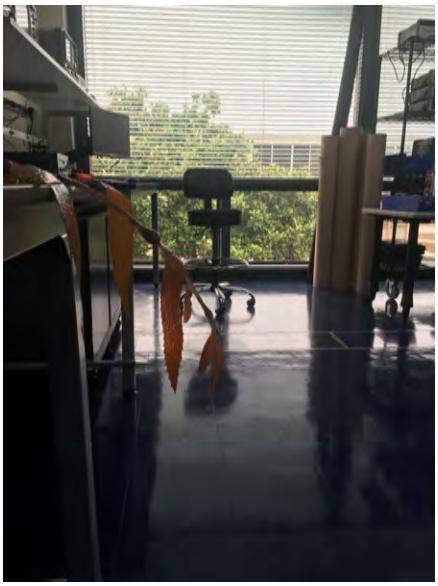

Figure C.12. Synthetic Giant Kelp Deflection at 12 inches.

Figure C.13. Real Giant Kelp Deflection at 1 inch.

Figure C.14. Real Giant Kelp Deflection at 2 inches.

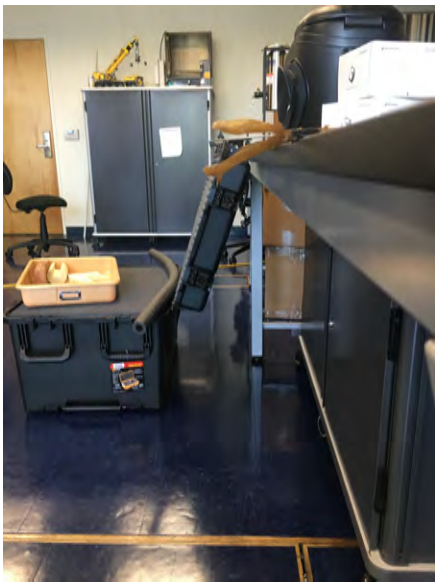

Figure C.15. Real Giant Kelp Deflection at 3 inches.

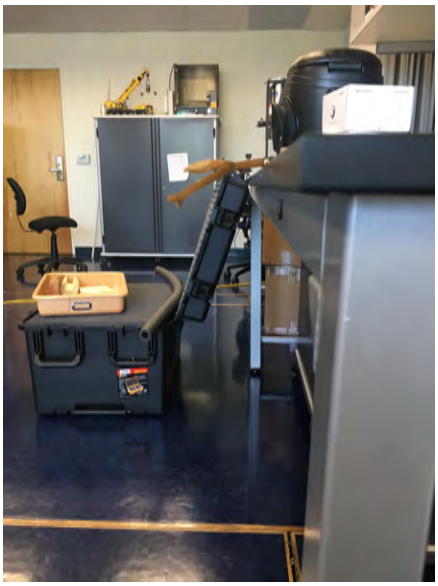

Figure C.16. Real Giant Kelp Deflection at 4 inches.

Figure C.17. Real Giant Kelp Deflection at 5 inches.

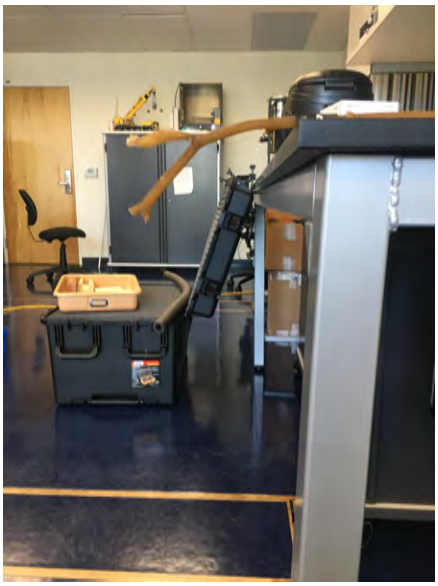

Figure C.18. Real Giant Kelp Deflection at 6 inches.

Figure C.19. Real Giant Kelp Deflection at 7 inches.

Figure C.20. Real Giant Kelp Deflection at 8 inches.

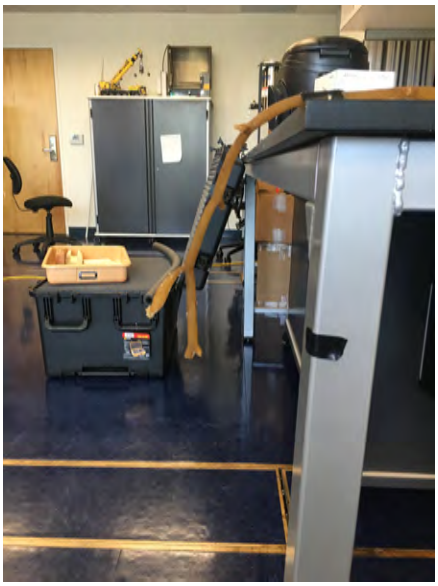

Figure C.21. Real Giant Kelp Deflection at 9 inches.

Figure C.22. Real Giant Kelp Deflection at 10 inches.

Figure C.23. Real Giant Kelp Deflection at 11 inches.

Figure C.24. Real Giant Kelp Deflection at 12 inches.

Table C.1 shows the kelp deflection results.

Table C.1. Deflection of the Synthetic and Real Giant Kelp Samples.

Length Suspended (cm)	Real Giant Kelp Deflection (cm)	Synthetic Giant Kelp Deflection (cm)
2.54 ± 0.15875	no deflection	no deflection
5.08 ± 0.15875	0.15875 ± 0.15875	0.3175 ± 0.15875
7.62 ± 0.15875	3.33375 ± 0.15875	2.54 ± 0.15875
10.16 ± 0.15875	4.92125 ± 0.15875	3.33375 ± 0.15875
12.7 ± 0.15875	6.985 ± 0.15875	5.55625 ± 0.15875
15.24 ± 0.15875	7.62 ± 0.15875	7.62 ± 0.15875
17.78 ± 0.15875	13.335 ± 0.15875	8.73125 ± 0.15875
20.32 ± 0.15875	16.51 ± 0.15875	10.16 ± 0.15875
22.86 ± 0.15875	19.20875 ± 0.15875	10.63625 ± 0.15875
25.4 ± 0.15875	20.79625 ± 0.15875	13.97 ± 0.15875
27.94 ± 0.15875	23.8125 ± 0.15875	17.30375 ± 0.15875
30.48 ± 0.15875	26.035 ± 0.15875	21.2725 ± 0.15875

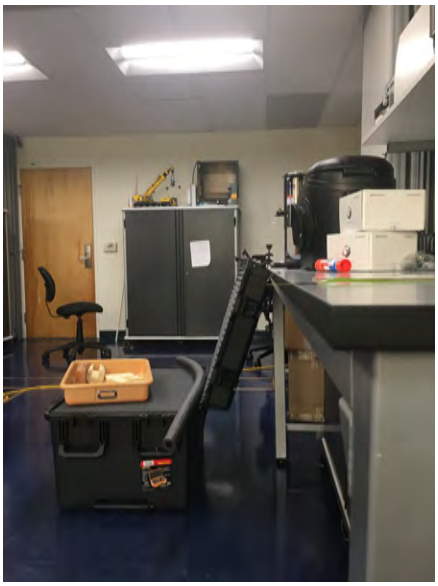

Figure C.25. Eelgrass Deflection at 1 inch.

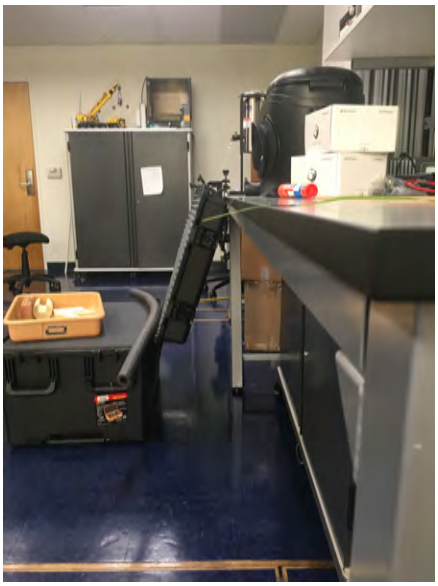

Figure C.26. Eelgrass Deflection at 2 inches.

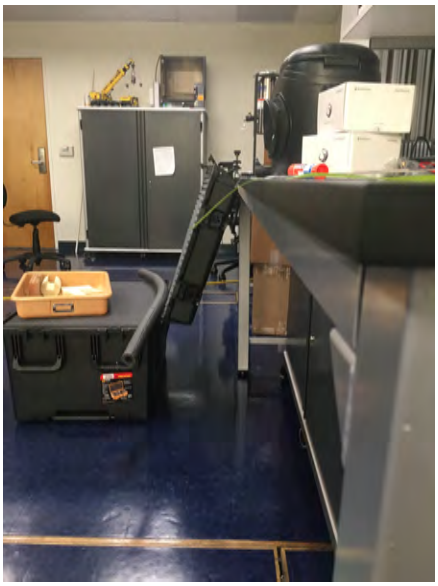

Figure C.27. Eelgrass Deflection at 3 inches.

Figure C.28. Eelgrass Deflection at 4 inches.

Figure C.29. Eelgrass Deflection at 5 inches.

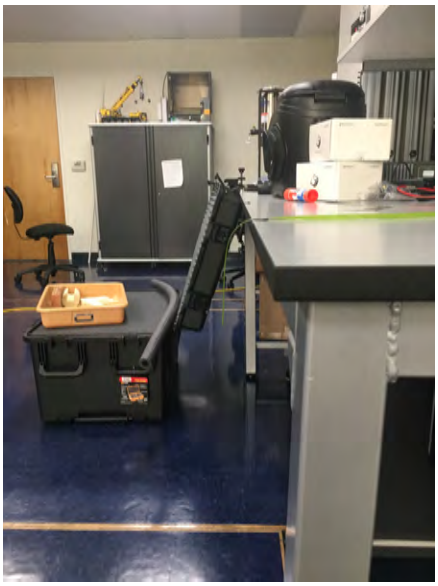

Figure C.30. Eelgrass Deflection at 6 inches.

APPENDIX D:
Custom Adapter for REMUS

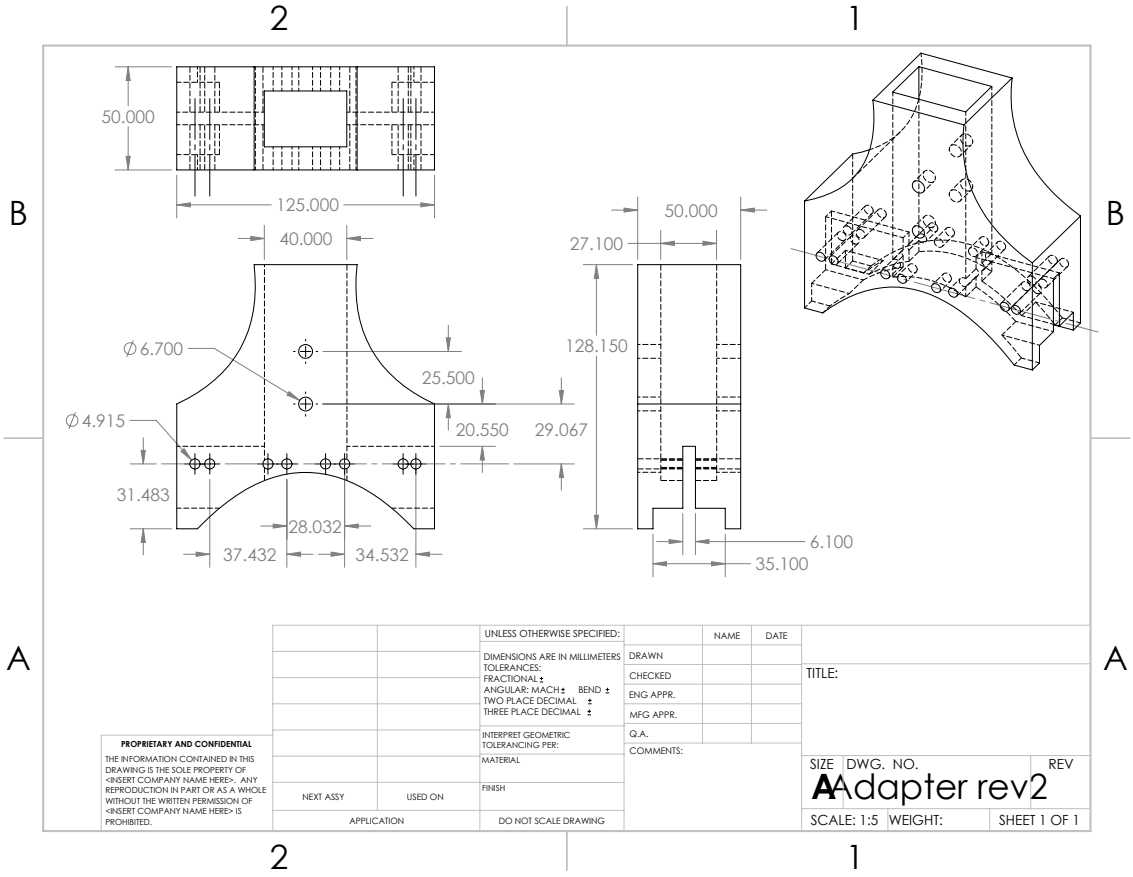

Figure D.1. Engineering Drawing for the REMUS Adapter.

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