Design of a Rotating Brush Underwater Grooming Device with a Focus on
Brush Optimization, Motor Control and Design for Reliability

by

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ABSTRACT

Title: Design of a Rotating Brush Underwater Grooming Device with a Focus on Brush Optimization, Motor Control and Design for Reliability

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The design and control of Remotely Operated Vehicles (ROV) to groom or clean the underwater surface of ship hulls is becoming an important aspect of the maintenance of vessels to the United States Navy. The biological growth below the waterline of the vessels can be the cause for drag penalties near 21% causing up to 32% increase in shaft power at 15 knots (Schultz, 2007). Research conducted by the Center for Corrosion and Biofouling Control at Florida Institute of Technology (FIT) indicated that weekly grooming can prevent high profile biological growth (Hearin, et al., 2015).

The design of a rotating brush grooming device for use underwater was based on both laboratory and field tests. The results from laboratory testing generated a new suction brush design that determined the brush torque is related to the suction force. A system identification test was also conducted in the lab using a Brushless Direct Current (BLDC) Motor and a direct link was determined between the error in the mathematical model and the changes in torque requirements. Comparing the power data from the laboratory and field tests determined that the motor power is related to the amount of fouling. A full-scale prototype grooming system was built and tested at Port Canaveral and was driven by a SeaBotics Remotely Operated Vehicle on test panels deployed in the saltwater environment. This demonstrated that the suction brushes were capable of attachment and effective removal of biological fouling. This data determined the necessary design requirements of 1.5 Newton-meter (N-m) torque and the ability to set a fixed RPM using a closed loop BLDC motor speed controller. The addition of Pareto analysis and design for reliability during the design phase allowed for the addition of three components to increase the time between mission failure from 814 hours to 9,030 hours.
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List of Abbreviations

BLDC: Brushless DC
EC: Electronic Commutation
CFD: Computational Fluid Dynamics
COTS: Commercial Off The Shelf
DAQ: Data Acquisition
DC: Direct Current
EMF: Electromotive Force
EMI: Electromagnetic Interference
FIT: Florida Institute of Technology
FMECA: Failure Mode Effects and Criticality Analysis
FPM: Feet per Minute
I/O: Input and Output
I2C: Inter-Integrated Circuit
LCD: Liquid Crystal Display
LDV: Laser Doppler Velocimeter
LED: Light Emitting Diode
MTBCF: Mean Time Between Critical Failure
MTBF: Mean Time Between Failure
NPRD: Nonelectronic Parts Reliability Database
PEM: Prediction Error Minimization
PUG: Push Underwater Grooming

ROV: Remotely Operated Vehicle

RPM: Revolution Per Minute

RTC: Real Time Clock

SD: Secure Digital

TTL: Transistor-Transistor Logic

VFD: Variable Frequency Drive

ZrO2: Zirconium Dioxide
Acknowledgement

I would personally like to thank Dr. Swain for his help and support through this process and for his guidance.
Dedication

This is dedicated to my loving wife Cat, our daughter Charlotte and our soon to be daughter Leighton. Thank you for your love and patience and for always being my guiding beacon.
Objective
Design an underwater grooming device with a rotating brush to proactively maintain ship hull coatings free of biofouling.

Requirements
1. This device shall be capable of attachment to the hull surface as well as the grooming using a single brush for both action.
2. A waterproof housing shall be designed and built for use in a saltwater environment.
3. The grooming device shall be capable of remote operation and data collection for post operation data analysis.
4. The power requirements should remain below 1000W using no more than a 24V supply.
5. The device should be portable and easily deployed from a vessel.

Hypotheses
1. The reduction in brush torque is related to the attachment force of the brush.
2. The grooming brush is capable of attachment force and effective grooming of biological fouling defined as a clean surface through visual inspections.
3. The power requirements of the grooming powertrain are related to the level of biological fouling when comparing a clean plate to a plate with biological fouling.
4. The Mean Time Between Critical Failure (MTBCF) of a grooming system can be improved by a factor of ten with the inclusion of no more than five components with the use of Pareto analysis.
Chapter 1 – Introduction

Grooming is defined as the proactive cleaning of a ship hull to prevent the growth of high profile fouling (Tribou, 2010). A grooming system is comprised of the attachment device and cleaning device. Previous research was conducted to develop a system combining both devices to reduce the overall power requirements. Previous research conducted by Michael Harper led to a rotating brush design that was used for cleaning and attachment to the hull. The research and information herein covers new brush research and the design and development of motor controls for a remotely operated grooming vehicle. The final area of research covers the reliability prediction of the grooming tool during the design of the final grooming tool.

Beginning with the optimized brush design the research was focused on further development of the rotating brush and the electric drive system and controls. The research also transitioned the brush from the controlled lab environment to the field where the brushes were tested on a moving platform across submerged plates at Port Canaveral. The results of these field tests provided information about the brush behavior as well as the power consumption information for each motor. Data and information obtained from these tests allowed for a greater understanding of the grooming system.

Work was conducted in the lab to test different variations of brush designs and to understand their characteristics. Additionally, tests were conducted to complete a system identification model of a BLDC motor during grooming conditions. These tests were conducted with an entry level CrustCrawler motor. The system identification tests allowed for insight into the interactions between the brush and motor and a better idea of the motor and controller combination required for the proper control of the rotating brush. These tests were conducted using a copper
ablative and a silicone fouling release coating because they are both qualified for use on US Navy vessels (Tribou, 2015).

The final area of analysis focused on the reliability of the system and understanding the Mean Time Between Failure (MTBF) and Mean Time Between Critical Failure (MTBCF) of the system as well as creating a Failure Mode Effects and Criticality Analysis (FMECA) report. This allows for an understanding of the system reliability during the design phase to enable modifications to ensure the best possible system. The last portion of the reliability analysis is to use the Pareto analysis method for the design phase instead of the standard usage for failure analysis.

The entire project involved both scientific and engineering processes to complete the final design. The more experimental science portion was conducted during the initial phases of testing for the brush designs and initial motor testing. The engineering design portion was started after the basic research was conducted to design the drivetrain, waterproof housing, motor controller and data logging system. Figure 1 shows a breakdown of the combination of processes used to combine both areas of the project.
Figure 1: Underwater Grooming Design and Research Philosophy
Chapter 2 – Background

The research was a continuation of work conducted by Michael Harper to develop a rotating suction brush for use cleaning ship hulls. The previous testing and research focused on the brush diameter, tuft angle and shroud material.

2.1 Existing Hull Cleaning Brush Research

2.1.1 Brush Design

Existing brush and grooming technology are designed for a more aggressive cleaning approach to remove high profile hard fouling such as the brush in Figure 2. The work conducted previously on this project was centered around designing a brush that can remove soft fouling through a proactive grooming approach.

Figure 2: SCAMP Cleaning Brush (Harper, 2014)

The previous research was focused on designing a brush that was the most efficient and produced the greatest amount of suction force with the smallest power requirement. The first phase was to determine the most efficient brush diameter for
the grooming process (Figure 3). The brush diameter tests concluded that the most efficient brush had a 10.2 cm diameter. The next phase was to research the optimized shroud design for the grooming brush. The three shroud materials were: Polyvinyl Chloride (PVC), rubber and a brush tuft shroud. Testing determined that the PVC shroud was the ideal design however it could possibly damage the hull coating (Figure 4). The rubber shroud also performed slightly better than the brush shroud however it was also determined that this could wear the coatings and decrease the coating longevity (Figure 5). Therefore, it was determined that a staggered outer row of brush tufts would be the top design for attachment force and power consumption (Figure 6).

Figure 3: Different Brush Diameters Used for Testing (Harper, 2014)

Figure 4: Brush with PVC Shroud (Harper, 2014)
After further testing and optimization analysis determined from the data that the most efficient suction brush used two rows of crenulated tufts. The brush was 10.2 cm in diameter with 30° tufts for the grooming (inner) row and 15° for the shroud (outer) row of tufts. (Harper, 2014).
2.1.2 Brush and Coating Interaction

One of the primary design goals of previous grooming brush research is to ensure the brush does not cause coating damage. The brush tribology studies the understanding of the interaction between the grooming brush and coating damage. Accelerated coating tests (Figure 7) were completed to visually determine the effects of the brush and coating interaction.

The results of previous research showed that the use of polypropylene with the correct stiffness shows no signs of surface marring (Tribou, 2015). The brushes must be conditioned to ensure the tips of each tuft filament are rounded to ensure new brushes do not cause coating damage.

2.2 Brush Hydrodynamics

One area not covered during the previous research was understanding the hydrodynamic behavior of the rotating brush. Hydrodynamics of a rotating body have been heavily researched but not with a rotating brush. A literature research was conducted to understand the flow regimes to better understand how the brushes could be designed to optimize the brush design. The rotating grooming brushes
behave like a common rotor-stator configuration the difference being that the shroud is attached to the rotor instead of the stator. The shroud is a permeable surface because it is made from two rows of bristle tufts spaced 15 degrees from each other as seen in Figure 6. The outer row of bristle tufts are staggered from the inner row and only half of the height of the inner row of bristles. An important aspect of this research is to determine a brush design that is the most efficient and requires the least amount of power from the motors.

The brush geometry and configuration are very important to determine the behavior of the internal flow. The aspect ratio of the cavity and Reynolds number of the flow allow for the determination of the flow characteristics. The similar configuration to the rotating grooming brush can be found in Figure 8 where it shows the dimensions used for determining the aspect ratio and Reynolds number.

![Figure 8: Rotor Stator Configuration Used During the Literature Research (Launder, Poncet, & Serre, 2010)](image)

The Reynolds number and aspect ratio values allow for the identification of the flow regimes in Figure 9. These different flow regimes allow for further
understanding of how the fluid circulates in a rotor-stator configuration. Table 1 describes the flow behavior of each regime.

![Figure 9: A Plot of the Four Flow Regimes for Rotating Cavity Flows (Lauder, Poncet, & Serre, 2010)](image)

Table 1: Flow Regimes for a Rotor-Stator Configuration (Lauder, Poncet, & Serre, 2010)

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<td>I</td>
<td>Laminar flow with merged boundary layers</td>
</tr>
<tr>
<td>II</td>
<td>Laminar flow with unmerged boundary layers</td>
</tr>
<tr>
<td>III</td>
<td>Turbulent flow with merged boundary layers</td>
</tr>
<tr>
<td>IV</td>
<td>Turbulent flow with unmerged boundary layers</td>
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Each of the regimes in Table 1 have different flow characteristics that are used to understand the flow behavior. The merged boundary layers of Regime I and Regime III are indicative of a torsional Couette flows with centrifugal outflow on the rotor and centripetal inflow on the stator (Haddadi & Poncet, 2008). The unmerged boundary layers of Regime II and Regime IV are typical of Batchelor flows with the similar centrifugal outflow on the rotor and inflow on the stator. The
other attribute of Batchelor flows in the presence of a region of fluid between the unmerged boundary layers with zero velocity inwards or outwards and a constant rotational velocity (Haddadi & Poncet, 2008).

The primary difference between the literature research and the current brush research lies in the shroud geometry. Other research involves an impermeable rigid body whereas the rotating brush has a permeable wall of brush tufts that require different assumptions. However, the literature provides insight to the flow behaviors to assist the understanding and design of grooming brushes.

2.3 Brushless DC Motor Overview

A BLDC motor is different from a standard DC motor due to the lack of electrical brushes. The BLDC motor is a synchronous motor with permanent magnets on the rotor and windings on the stator. An electrical torque is applied to the rotor by a rotational magnetic field on the stator. The rotational magnetic field is achieved through Electrical Commutation (EC) which energizes the stator windings causing the rotor to chase the moving electromagnetic poles of the stator (Akin & Bhardwaj, 2013). Figure 10 shows a simplified model for a three-phase motor with a single pole rotor.

![Figure 10: Three Phase Synchronous BLDC Motor (Akin & Bhardwaj, 2013)](image-url)
The commutation signal that is delivered to the BLDC motor from the motor controller is a trapezoidal shape. The same trapezoidal shape is also present for the Back-Electromotive Force (back-EMF) signals. The purpose of the trapezoidal shape is to generate the highest possible torque and theoretically produce a constant torque output seen in Figure 11.

![Electrical Waveforms and Torque for a Three Phase BLDC](image)

**Figure 11: Electrical Waveforms and Torque for a Three Phase BLDC (Akin & Bhardwaj, 2013)**

### 2.4 Grooming Brush Motors

One of the requirements is to develop a tool which uses less than 1000W of power with a power source no greater than 24V. To prevent the addition of a further current protection system the maximum DC voltage is 30V with a nominal safe voltage of 24V (International Marine Contractors Association, 2010).

#### 2.4.1 Push Underwater Grooming (PUG) Maxon Motor Drive

Previously developed grooming devices used a variety of different motor options to provide the necessary rotational torque for grooming. The first grooming tool developed at FIT was PUG as seen in Figure 12. This device utilized a 32mm flat
BLDC motor from Maxon Motor. A custom gearbox was made on campus to drive a set of five grooming brushes. The motor required an oil filled housing to prevent saltwater intrusion during testing. This system functioned well but the single motor design limited the data collection because the brushes could not be individually controlled.

![PUG Device with Maxon Motor Driven Brushes](image)

*Figure 12: PUG Device with Maxon Motor Driven Brushes (Harper, 2014)*

### 2.4.2 Crust Crawler Underwater Thruster Motors

For the development of the new grooming tool the brushes would need to be independently powered to maintain precise control of each brush to understand the behavior of a single brush. Through some research, a hobby thruster company was found that produced brushless underwater thruster motors. These motors were ideal for the testing due to their low costs and ability to run underwater at voltages between 12 – 24V while collecting the required data. The motors were controlled using a Castle Creations motor controller which functioned at a distance from the motor allowing for the controllers to be located at the surface. The BLDC motors function as sensorless BLDC motors therefore the controller sends commutations timed against the back-EMF signals. The data from each motor was offloaded from the motor controller using the Castle Creations CastleLink software.
The first motor tested was a 400W motor (Figure 13) that required a 5:1 gearbox to rotate the grooming brush. This motor, combined with the gearbox provided the necessary torque to rotate the brush, however, the system is overly complicated due to the alignment of the motor and gearbox.

![Figure 13: The Crust Crawler 400W Motor with 5:1 Gearbox](image)

The other Crust Crawler motor was the 600W version (Figure 14) with an integrated 4.28:1 gearbox. This motor was oil compensated which allowed for better performance at high powers due to heat transfer. Also, this motor had a much higher torque output allowing for a direct connection between the motor and grooming brush. The higher torque greatly simplified the system and removed variables from the testing procedures. The 600W motor was used heavily throughout testing before determining the final combination moving forward.
2.5 Design for Reliability

System reliability is defined as the probability that a specific system will be able to provide the expected functions (Roush & Webb, Applied Reliability Engineering Volume II, 2001). The reliability of a system is dependent upon environment and end user requirements. Typically for military use the lifespan of a system must be at least 10 years and perform in the most extreme environments while ensuring the lowest costs while maintaining the highest level of performance (Reliability Information Analysis Center; Data and Analysis Center for Software, 2005). To ensure these criteria are successfully satisfied the design of the system must have the proper redundancies and components choices.

An example of design for reliability is the design of the O-ring seals that were used on the solid rocket boosters for the Space Shuttle system. The original design called for a single O-ring at each joint (Figure 15). Further into the design phase it was determined that a failure would cause a catastrophic failure which led to a design change and a redundant secondary O-ring (Figure 16) was added to each seal interface (Leemis, 2009). It is important to ensure that redundant components are independent of each other and that a single failure will not cause both redundant
systems to fail. Unfortunately, an assumption was made that the redundant O-rings were independent, however, under certain environmental conditions this assumption is false. This reliability oversight during the design phase led to the tragic Space Shuttle Challenger accident on January 28, 1986.

![Figure 15: Six O-ring Series Arrangement (Leemis, 2009)](image)

A common method to conduct reliability analysis after deployment of the system is with the use of Pareto analysis for system improvement. The Pareto Principle suggests that the majority of the reliability losses are not evenly distributed and a small number of components have a large contribution to the overall reliability prediction (Roush & Webb, Applied Reliability Engineering Volume I, 2002). This analysis helps to identify the highest drivers that could negatively impact the overall probability of system success. The Pareto analysis is completed visually using a bar graph to show the number of failures for a particular component or failure mode. A line graph is overlaid to show a cumulative percentage of each data set.
Chapter 3 – Test Apparatuses and Methodology

3.1 Test Apparatuses

3.1.1 Test Tank

The first test apparatus was the test tank in the lab used to measure the suction forces of the brushes and to test the grooming system in a controlled environment. The tank and frame allowed for a Variable Frequency Drive (VFD) motor to be mounted to the tank for testing the brush torque and suction forces. When testing the suction forces, a neutrally buoyant plate was placed below the brush. The plate was mounted on four threaded guide rods with Delrin sleeves ensuring an extremely low friction interface. A force gauge was mounted to a constant velocity tensile tester and attached to the plate using non-stretch line. The tensile tester ensured consistent force application for the different suction force tests.

The tank was also used for the system identification of the BLDC motor and brush system. The system identification tests used the VFD motor platform with an adapter to install the CrustCrawler 600W motor.

Using the same test tank, further brush research was conducted alongside electric motor testing for the motors to rotate the brushes at variable speeds. The initial motors used for testing were CrustCrawler underwater BLDC thruster motors. These motors allowed for remote operation and data collection of: Revolution Per Minute (RPM), amperage, voltage and throttle position. Before the CrustCrawler test platform was brought to field testing it was tested for proper function in the lab tank (Figure 17).
3.1.2 Test Plates

The next test apparatus were the test plates (Figure 18) located at Port Canaveral, Florida. These plates were constantly immersed in the saltwater and have constant soft and hard fouling pressure. This field environment allowed for accurate testing of the environments that a grooming vehicle will operate. Testing the grooming tool on the submerged plates allowed for the quantification of fouling removal rates for different grooming brushes.
The tests were conducted with the grooming tool mounted on a SeaBotics ROV (Figure 19) to ensure constant translation across the plate. The ROV attached to the test plate using a VRAM to generate the necessary suction forces. During the tests the brushes were rotated at different RPM and different directions to understand the grooming behavior. The grooming tool was designed to be neutrally buoyant to ensure that the only force on the ROV is generated by the rotation of the grooming brushes.
3.2 Methodology

3.2.1 Individual Brush Testing

Each of the brushes were tested at 9 different RPMs from 300 – 1100 RPMs in 100 RPM increments. A VFD motor was used for these tests to ensure a constant RPM at all levels of torque. A FUTEK torque meter was used to obtain the torque reading for each brush at each RPM. The suction force was obtained using a force gauge attached to a constant velocity tensile tester that measured the force applied on a plate as it is pulled away from the brush. Figure 20 shows the line that pulls that plate away from the rotating brush. The plate is made neutrally buoyant using the foam on either side and it slides on a near frictionless Delrin interface.
3.2.2 System Identification

To better understand the physics behind the BLDC motor a system identification was run on the system. The CrustCrawler motor was outfitted with current sensors, voltage sensors, a rotary encoder and a torque meter. The system was calibrated and then tests were run with the data acquisition completed using a real-time Texas Instruments Data Acquisition (DAQ) system and the MATLAB data acquisition toolbox. This information was then added to a mathematical state space model of the BLDC grooming motor. Figure 21 shows a diagram of the Crust Crawler 600 motor outfitted with current and voltage sensors feeding the DAQ system. This system was first run with a compressed brush on an epoxy baseline surface in the air. Then the same tests were run under the same compression with the grooming brush on different surfaces while being submerged.
An important area of system identification is the input signal used during the testing because this signal should assess different motor ranges. The signal sent to the motor was a pseudo random signal manually generated to cover short and long periods of rotation. The signal was generated and saved in the BLDC motor controller for a consistent random signal throughout each test. The data from the DAQ system was then applied to the mathematical model to better understand the BLDC motor during grooming. The first portion of the data collection was understanding the parameters of the BLDC motor by running the motor and estimating the motor parameters until the model curve matched the actual data curve. Once these values were determined they were locked into the set of equations used throughout the validation and testing stages of the test. The variation of the measured data compared to the state space model can then be quantified as the effect of grooming on the system.

Figure 21: CrustCrawler 600 BLDC Motor System Identification Test Setup
The data collected from the sensors through the DAQ system and MATLAB were fed into a system of equations to determine the parameters of the BLDC motor. The following equations were used in the MATLAB program for the three phase BLDC motor (Kumari, Laxminarayana, & Tarakalyani, 2013):

\[ v_{ab} = R(i_a - i_b) + L \frac{d}{dt}(i_a - i_b) + e_a - e_b \]  
(1)

\[ v_{bc} = R(i_b - i_c) + L \frac{d}{dt}(i_b - i_c) + e_b - e_c \]  
(2)

\[ v_{ca} = R(i_c - i_a) + L \frac{d}{dt}(i_c - i_a) + e_c - e_a \]  
(3)

\[ T_e = k_f \omega_m + J \frac{d\omega_m}{dt} \]  
(4)

This set of equations can be simplified by eliminating one using the relationship between the three phase currents shown in Eq. 3. The following two equations will allow for the calculation of the combined phase voltages:

\[ i_a + i_b + i_c = 0 \]  
(5)

\[ v_{ab} = R(i_a - i_b) + L \frac{d}{dt}(i_a - i_b) + e_a - e_b \]  
(6)

\[ v_{bc} = R(i_a - 2i_b) + L \frac{d}{dt}(i_a - 2i_b) + e_b - e_c \]  
(7)

To determine the back-EMF for each phase, a MATLAB function was built to calculate the phase shift between each of the three phases. The shift between each phase was calculated using a built trapezoidal waveform function (Appendix E). The following equations were used to calculate the phase back-EMF:
\[ e_a = \frac{k_e}{2} \omega_m F(\theta_e) \]  \hspace{1cm} (8)
\[ e_b = \frac{k_e}{2} \omega_m F\left(\theta_e - \frac{2\pi}{3}\right) \]  \hspace{1cm} (9)
\[ e_c = \frac{k_e}{2} \omega_m F\left(\theta_e - \frac{4\pi}{3}\right) \]  \hspace{1cm} (10)
\[ T_e = \frac{k_t}{2} \left[ F(\theta_e) i_a + F\left(\theta_e - \frac{2\pi}{3}\right) i_b + F\left(\theta_e - \frac{4\pi}{3}\right) i_c \right] \]  \hspace{1cm} (11)

With these calculations, a system of linear equations can be generated. From this set of linear equations there will be unknown parameters that will need to be estimated and through an iterative process them values can be determined using the prediction error minimization (PEM) algorithm in MATLAB. The following set of equations are the system of linear state space equations:

\[
\begin{pmatrix}
\dot{i}_a \\
\dot{i}_b \\
\omega_m'
\end{pmatrix}
= \begin{pmatrix}
\frac{-R}{L} & 0 & 0 & 0 \\
0 & \frac{-R}{L} & 0 & 0 \\
0 & 0 & -\frac{k_f}{J} & 0 \\
0 & 0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
i_a \\
i_b \\
\omega_m \\
\theta_m
\end{pmatrix}
+ \begin{pmatrix}
\frac{2}{3L} & 0 \\
0 & \frac{1}{3L} \\
0 & 0 & \frac{-1}{J} \\
0 & 0 & 0 & 0
\end{pmatrix}
\begin{pmatrix}
v_{ab} - e_{ab} \\
v_{bc} - e_{bc} \\
T_e - T_L
\end{pmatrix}
\]  \hspace{1cm} (12)

\[
\begin{pmatrix}
i_a \\
i_b \\
i_c \\
\omega_m \\
\theta_m
\end{pmatrix}
= \begin{pmatrix}
1 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 \\
-1 & -1 & 0 & 0 \\
0 & 0 & 1 & 0 \\
0 & 0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
i_a \\
i_b \\
i_c \\
\omega_m \\
\theta_m
\end{pmatrix}
\]  \hspace{1cm} (13)

Where,
- \( v \): Phase to phase voltage
- \( R \): Resistance for each phase
- L: Inductance of each phase
- i: Phase current
- e: Phase back-EMF
- Te: Electric torque
- kr: Torque constant
- ke: Back-EMF constant
- ωm: Angular velocity of the motor
- J: Rotor inertia
- θe: Electric angle of rotor
- \( F(θe) \): Back-EMF as a function of rotor position

The state space equations (Eq. 12 and Eq. 13) use the inputs from the DAQ inputs to create the output values for the BLDC model. The inputs into the state space model in Eq. 12 are:

- Phase A and Phase B Current
- Shaft Velocity
- Shaft Position
- Phase A to Phase B Voltage
- Phase B to Phase C Voltage
- Phase A to Phase B Back EMF
- Phase B to Phase C Back EMF
- Electrical Torque
- Load Torque

The outputs of the model are determined from Eq. 13 using the outputs obtained from Eq. 12. The model outputs are the following:

- Phase A, Phase B and Phase C Current
3.2.3 Field Testing
After lab verification, the grooming system was taken to the field to groom the submerged plates. The grooming tool was attached to the ROV and the complete system conducted successful tests at Port Canaveral. The ROV was programmed to move across the plate at 0.5 m/s and the brush data was recorded for each test. The behavior of the system was recorded on the straights and while turning using video cameras and diver information. Before and after photos were taken to determine the grooming effectiveness. Figure 22 shows a swath of clean plate at Port Canaveral after one pass with the grooming tool. The test plates are lined with marks every 2 feet in both the horizontal and vertical direction.

![Figure 22: A Clean Swath of the Intersleek 900 Fouling Release Coating at Port Canaveral](image)
3.2.4 Reliability

The reliability of the system was determined using a FMECA and a Reliability Block Diagram (RBD) to understand the overall system and discover critical failure modes. The reliability of each component was determined using the Nonelectronic Parts Reliability Database (NPRD) and supplier data and a roll up of the failure rates and MTBF were obtained. The RBD allowed for a roll up of the MTBF values to determine the MTBCF. The FMECA was completed per DI-SESS-81495A on a functional level to determine the probability of a component of the system failing and the effects of a specific failure mode. The ground rules for the FMECA are as follows:

- Only single failures are considered
- All inputs are considered correct
- Device is operating within the designed limits
- Maintenance induced failures are not considered

The FMECA identifies all possible failure modes for each component and the effects of each failure mode. The failure modes are then graded by their criticality and effect on the different mission segments: Pre-Deployment, Deployment, Operation and Retrieval. The specific failure mode was analyzed by determining the failure probability and severity of the failure. The probability of a failure mode was calculated using a percentage of the failure rate of the component. The percentages were determined using a normal distribution which evenly splits the failure rate between all the failure modes. The probability of a failure is calculated with Eq. 14 and each failure mode probability was ranked within five levels listed in Table 2.

$$P_i(t) = 1 - e^{-\lambda_i t}$$ (14)
\[ \lambda_i = \frac{1}{\text{MTBF}_i} \]  \hspace{1cm} (15)

Where:

- \( P_i(t) \): Component probability of failure
- \( \lambda_i \): Component failure rate
- \( \text{MTBF}_i \): Component Mean Time Between Failure
- \( t \): Mission duration in hours

<table>
<thead>
<tr>
<th>Level</th>
<th>Frequency</th>
<th>Probability Bounds</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Frequent: High probability of occurrence</td>
<td>( P \geq 10^{-1} )</td>
</tr>
<tr>
<td>B</td>
<td>Reasonably Probable: Occasional probability of occurrence</td>
<td>( 10^{-2} \leq P \leq 10^{-1} )</td>
</tr>
<tr>
<td>C</td>
<td>Occasional: Occasional probability of occurrence</td>
<td>( 10^{-3} \leq P \leq 10^{-2} )</td>
</tr>
<tr>
<td>D</td>
<td>Remote: Remote probability of occurrence</td>
<td>( 10^{-6} \leq P \leq 10^{-3} )</td>
</tr>
<tr>
<td>E</td>
<td>Extremely Unlikely: Extremely small probability of occurrence</td>
<td>( P \leq 10^{-6} )</td>
</tr>
</tbody>
</table>

The severity of each failure mode was categorized into four different categories. The overall severity used the worst severity from the four different mission segments. Category I and Category II are considered as critical and will cause a mission failure (Department of Defense, 1980). The severity categories listed in Table 3 display the guidelines for properly categorizing each failure mode.
### Table 3: Severity Categories for Determining Risk (Naval Air Systems Command, 2014)

<table>
<thead>
<tr>
<th>Category</th>
<th>Severity</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Catastrophic: Failure that may result in death or system loss</td>
</tr>
<tr>
<td>II</td>
<td>Critical: Failure that may result in serious injury, major system damage, or mission loss</td>
</tr>
<tr>
<td>III</td>
<td>Marginal: Failure that may cause injury, minor system damage, or mission degradation</td>
</tr>
<tr>
<td>IV</td>
<td>Minor: Failure not serious enough to cause injury but causes unscheduled maintenance</td>
</tr>
</tbody>
</table>

If a failure mode is determined to cause a single point failure or loss of mission, then a compensating provision must be added or it must be proven that the probability of occurrence is Level D or Level E.

The final portion of the reliability analysis was to complete a reliability block diagram to obtain a visual representation of the system using series and parallel connections. The final reliability obtained from this diagram is the Mean Time Between Critical Failure (MTBCF). The MTBCF is the average time between failures that would cause a mission abort or loss of system. The reliability of each component was calculated using a 23-hour mission time to determine the probability of mission success (Tribou, 2015). The first portion determined the reliability of each component using the following equations (Ebeling, 2009):

\[
R_i(t) = e^{-\lambda_i t} \tag{16}
\]

- \( R_i(t) \): Component Reliability as a function of time
To complete these calculations the components in parallel connections were combined to generate one reliability. During this combination process it is important to determine the number of components in the redundant parallel segment that must remain functioning for system success. For “n” total components and “m” required for mission success a binomial reliability function is applied using Eq. 17 (Roush & Webb, Applied Reliability Engineering Volume II, 2001).

For Eq. 17 to function properly the redundant components must have the same reliability. A simple example of a parallel system with two components with one component required for mission success can be found in Eq. 18. Eq. 18 will also work for components with different reliabilities.

\[
R_p(t) = 1 - \sum_{i=0}^{m-1} \frac{n!}{i! (n - 1)!} R^i (1 - R)^{n-1}
\] (17)

\[
R_p(t) = (R_1 R_2) + [R_1 (1 - R_2)] + [(1 - R_1) R_2]
\] (18)

Once all the parallel segments are combined into a single reliability the series system is then combined to determine a final reliability using Eq. 19 (Ebeling, 2009).

\[
R_s(t) = \prod_{i=1}^{n} R_i(t)
\] (19)

- n: Total number of components in the parallel system
- m: Number of components required for system to function
- \( R_p \): Parallel system reliability
- \( R_s \): Series system reliability
The reliability block diagram also follows a set of assumptions to ensure consistent analysis for the entire grooming system. The following assumptions for the reliability block diagram follow the reliability design methods for NAVSEA systems. The assumptions are the following (NAVSEA Product Assurance Division, 1985):

- The lines connecting the blocks have no reliability values. The lines serve only to give order and direction to the diagram.
- Failure of any device denoted by a block in the diagram will cause failure of an entire product, except in those cases where alternate modes of operation are present such as parallel connections.
- Each component denoted by a block is independent, with regard to probability of failure of or due to all other blocks.
- No interface problems occur between man and product; all human elements are assumed to be completely reliable.

A Pareto analysis was conducted using a chart to visually show the distribution of component reliability. This process is generally completed once the system has been fielded to track component failures to change processes or create a case for design change. By completing this process during the design phase the same Pareto methods can be used to prevent design changes after the system has been implemented. The Pareto chart is used for the visual examination of each components failure rate as a bar chart. Another line graph is overlaid on a secondary access that shows the cumulative percentage of the failure rate for each component. Components with the higher failure rates will consume the majority of the failure rate percentage following the Pareto Principle. If any of these components are critical for mission success, then a compensating provision must be
implemented to ensure a single failure will not cause a mission failure. The determination of a critical component is determined with the use of the FMECA analysis. A compensating provision is an action or design change that negate or mitigate the effects of a failure within a system (Department of Defense, 1980).
4.1 Individual Brush Testing

From the literature research, lab and field testing a better understanding was obtained for different potential brush designs. Using the most efficient brush from previous research it was determined that the brush created too much suction force causing excess torque requirements due to friction between the brush and surface. The excess torque led to the testing of new brush designs to decrease the suction force while still allowing for efficient grooming and ample suction force to hold the tool to the ship’s hull. The first set of brushes are similar to the standard crenulated brush with varying shroud heights (Figure 23). The next set of brushes tested lined the grooming tufts up with the shroud tufts to allow fluid to exit the vortex within the rotating brush decreasing the suction force (Figure 24). The final set of brushes were designed to increase the efficiency of the brush by creating a smooth wall of grooming tufts (Figure 25). All three brush configurations were tested with different shroud tuft heights of: 0.3in, 0.4in, 0.5in and 0.6in.

Figure 23: Standard Grooming Brush with Staggered Grooming Tufts and Shroud Tufts
The different brush designs were all tested across a wide range of angular velocities from 300RPM (Figure 26) – 1100RPM (Figure 27) to get a full understanding of the brush behavior. The suction force and torque were collected and documented to understand the grooming brush powering requirements. Table 4: Suction Force and
Torque Values for Lab Tested Brush Variations

Table 4 shows the average torque and power requirements for each grooming brush design.

Figure 26: Brush Suction at 300RPM

Figure 27: Brush Suction at 1100RPM
Table 4: Suction Force and Torque Values for Lab Tested Brush Variations

<table>
<thead>
<tr>
<th>Brush</th>
<th>Tuft Layout</th>
<th>Average Suction Force (lbs.)</th>
<th>Torque (N-m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Standard Grooming Brush with 30° Inner Grooming Tufts with 0.3” tall</td>
<td>8.11</td>
<td>0.525</td>
</tr>
<tr>
<td></td>
<td>crenulated shroud tufts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Standard Grooming Brush with 30° Inner Grooming Tufts with 0.4” tall</td>
<td>8.72</td>
<td>0.521</td>
</tr>
<tr>
<td></td>
<td>crenulated shroud tufts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Standard Grooming Brush with 30° Inner Grooming Tufts with 0.5” tall</td>
<td>9.70</td>
<td>0.619</td>
</tr>
<tr>
<td></td>
<td>crenulated shroud tufts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Standard Grooming Brush with 30° Inner Grooming Tufts with 0.6” tall</td>
<td>10.37</td>
<td>0.379</td>
</tr>
<tr>
<td></td>
<td>crenulated shroud tufts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>30° Grooming Tufts with In-Line 15° Shroud Tufts 0.3” tall</td>
<td>7.67</td>
<td>0.431</td>
</tr>
<tr>
<td>6</td>
<td>30° Grooming Tufts with In-Line 15° Shroud Tufts 0.4” tall</td>
<td>7.60</td>
<td>0.463</td>
</tr>
<tr>
<td>7</td>
<td>30° Grooming Tufts with In-Line 15° Shroud Tufts 0.5” tall</td>
<td>8.06</td>
<td>0.493</td>
</tr>
<tr>
<td>8</td>
<td>30° Grooming Tufts with In-Line 15° Shroud Tufts 0.6” tall</td>
<td>9.21</td>
<td>0.470</td>
</tr>
<tr>
<td>9</td>
<td>30° Grooming Tufts Doubled with 15° Shroud Tufts 0.3” tall</td>
<td>8.11</td>
<td>0.397</td>
</tr>
<tr>
<td>10</td>
<td>30° Grooming Tufts Doubled with 15° Shroud Tufts 0.3” tall</td>
<td>8.17</td>
<td>0.515</td>
</tr>
</tbody>
</table>
### 4.1.1 Standard Crenulated Brush with Varying Shroud Heights

<table>
<thead>
<tr>
<th>Shroud Tufts 0.4” tall</th>
<th>30° Grooming Tufts Doubled with 15° Shroud Tufts 0.5” tall</th>
<th>30° Grooming Tufts Doubled with 15° Shroud Tufts 0.6” tall</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>11</strong></td>
<td>8.78</td>
<td>0.533</td>
</tr>
<tr>
<td><strong>12</strong></td>
<td>9.03</td>
<td>0.601</td>
</tr>
</tbody>
</table>

**Figure 28: Suction Force for the Standard Crenulated Grooming Brush with Varying Shroud Heights**
Figure 29: Torque for the Standard Crenulated Grooming Brush with Varying Shroud Heights

Figure 30: Attachment Coefficient for the Standard Crenulated Grooming Brush with Varying Shroud Heights
It was shown in Figure 28 that the greatest suction force is provided by the 0.6in shroud height and the lowest suction force was provided by the 0.3in shroud. This follows the previous assumptions that a longer shroud provides greater levels of suction force due to the larger area of the low-pressure region within the brush. The 0.6in shroud also causes for the greatest torque requirement and the 0.3in shroud requires the least amount of torque input. During testing, it was noticed near 700RPM the brush generated enough suction force for the outer shroud to make contact for the 0.6in shroud. This is the cause of the steeper torque slope from 700-1100RPM. When looking at the attachment coefficient plot it is clear the brush becomes the least efficient at the 700RPM mark. Overall, the standard crenulated brush with the 0.3in shroud is the most efficient after 500RPM, generates ample suction force and has the lowest torque requirement.

4.1.2 Grooming and Shroud Tufts In-Line with Varying Shroud Heights

![Figure 31: Suction Force for the In-Line Tuft Grooming Brush with Varying Shroud Heights](image)
Figure 32: Torque for the In-Line Tuft Grooming Brush with Varying Shroud Heights

Figure 33: Attachment Coefficient for the In-Line Tuft Grooming Brush with Varying Shroud Heights
Similar to the standard crenulated brush the 0.6in shroud provides that greatest suction forces across all angular velocities (Figure 31). It also requires the greatest amount of input torque and the 0.4in shroud requires the least amount of torque input (Figure 32). Due to the tuft geometry, the inner grooming tufts were supported by the outer shroud tufts which prevented the shroud tufts from making direct contact with the surface. This is clear when looking at the attachment coefficient in Figure 33 where the coefficient increases at 700RPM. The best shroud configuration for the in-line tufts is the 0.4in shroud tuft height because it is the most efficient and requires the least amount of input torque for grooming.

4.1.3 Double Number of Grooming Tufts with Varying Shroud Heights

![Graph of Suction Force for the Double Grooming Tuft Grooming Brush with Varying Shroud Heights](image)

*Figure 34: Suction Force for the Double Grooming Tuft Grooming Brush with Varying Shroud Heights*
Figure 35: Torque for the Double Grooming Tuft Grooming Brush with Varying Shroud Eights

Figure 36: Attachment Coefficient for the Double Grooming Tuft Grooming Brush with Varying Shroud Heights
The double grooming tuft brush has twice as much initial brush contact with the surface which causes very similar suction force results up to 800RPM (Figure 34) at which point the 0.6in shroud height is shown to produce the greatest suction force. However, unlike the other two brush configurations, the 0.5in shroud height requires the greatest amount of torque input (Figure 35). When looking at the attachment coefficient in Figure 36, we can see that all four shroud heights have similar behavior and efficiency other than at the 700RPM and 800RPM range where the 0.3in shroud produced the most efficient results. Comparing all the results the most efficient and highest performing brush is the 0.4in shroud with the tuft rows in-line with each other.

4.2 System Identification

The system identification yielded successful results and a mathematical model was generated for the BLDC motor system. This process allowed for the determination of the motor induction and resistance as well as a practical lesson in the physics behind the functionality of a BLDC motor.
Figure 37: Fit Data for the Phase Current for the Compressed Brush on Epoxy Plate in Air

Figure 38: Validation Data for the Phase Current for the Compressed Brush on Epoxy Plate in Air
Figure 39: Fit Data for the Velocity and Position for the Compressed Brush on Epoxy Plate in Air

Figure 40: Validation Data for the Velocity and Position for the Compressed Brush on Epoxy Plate in Air
After running the first test in air the same test was run with the compressed brush running on an epoxy plate in water. The two tests on the epoxy plate allowed for an understanding of the changing torque requirements due to interaction between the brush and water. The same tests were run with the following results:

Figure 41: Fit Data for the Phase Current for the Compressed Brush on Epoxy Plate in Water
Figure 42: Validation Data for the Phase Current for the Compressed Brush on Epoxy Plate in Water

Figure 43: Fit Data for the Velocity and Position for the Compressed Brush on Epoxy Plate in Water
The other process completed during the system identification testing involved a comparison between the epoxy plate in air and the epoxy plate in water. This was completed to determine the increase in torque on the brush due to the water. Both tests were completed with the same brush at the same level of compression using the parameters obtained during data fit portion of each test. This difference would be the inherent drag caused by the interaction between water and the brush. The differences between the two are most evident in Figure 40 and Figure 44 while looking at the position plots. In these plots the overall difference is determined from the final position data points on the validation plots. The percent difference is calculated with the following results below in Table 5.
Table 5: Epoxy Plate Brush Position Data Percent Difference Between Water and Air

<table>
<thead>
<tr>
<th>Data Point</th>
<th>Water (N-m)</th>
<th>Air (N-m)</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>152.7737</td>
<td>116.837</td>
<td>N/A</td>
</tr>
<tr>
<td>Test</td>
<td>157.5912</td>
<td>137.4696</td>
<td>N/A</td>
</tr>
<tr>
<td>Difference</td>
<td>4.8175</td>
<td>20.6326</td>
<td>76.65%</td>
</tr>
</tbody>
</table>

This leads us to believe that the difference in torque requirements was four times greater for a brush in water than a brush in air. This was confirmed when comparing the raw torque data for the epoxy plate in air and water in Figure 45. A torque measurement was collected near 5 seconds and 10 seconds and a percent difference was calculated and compared to the percent difference between the position plots in Table 6.

Figure 45: Epoxy Plate Torque Comparison Between Water and Air
Table 6: Epoxy Plate Torque Data Percent Difference Between Water and Air

<table>
<thead>
<tr>
<th>Time (Sec)</th>
<th>Water (N-m)</th>
<th>Air (N-m)</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0.36623</td>
<td>0.22431</td>
<td>63.27%</td>
</tr>
<tr>
<td>10</td>
<td>0.36165</td>
<td>0.19685</td>
<td>83.72%</td>
</tr>
<tr>
<td>Average</td>
<td>0.36394</td>
<td>0.21058</td>
<td>72.83%</td>
</tr>
</tbody>
</table>

Comparing the final percent difference of torque from Table 5 and Table 6 it is clear the error in the position plots are caused by the increase in torque due to water resistance on the brush. The percent difference between the position plots is within 4% of the percent difference of the torque requirements.

Once the baseline tests were completed on the epoxy plate both in air and submerged a submerged test was completed using IS700 fouling release coating and BRA 540 copper ablative coating.

![Figure 46: Fit Data for the Phase Current for the Compressed Brush on IS700 Plate in Water](image-url)
Figure 47: Validation Data for the Phase Current for the Compressed Brush on IS700 Plate in Water

Figure 48: Fit Data for the Velocity and Position for the Compressed Brush on IS700 Plate in Water
Figure 49: Validation Data for the Velocity and Position for the Compressed Brush on IS700 Plate in Water

Figure 50: Fit Data for the Phase Current for the Compressed Brush on BRA540 Plate in Water
Figure 51: Validation Data for the Phase Current for the Compressed Brush on BRA540 Plate in Water

Figure 52: Fit Data for the Velocity and Position for the Compressed Brush on BRA540 Plate in Water
From the tests on the IS700 and BRA 540 coatings we can learn more about the brushes behavior on these different coatings. On the fouling release coating, it can be seen that there was less static friction which can be seen by the smoother acceleration to the peak velocity (Figure 49) than the copper ablative coating in Figure 53. The plots from these two coatings gave further validation to the determination of the final system parameters that were the unknowns for the system of linear equations. The solutions for these parameters are the following:

\[
\begin{pmatrix}
-44.2201 & 0 & 0 & 0 \\
0 & -14.9271 & 0 & 0 \\
0 & 0 & -0.0015582 & 0 \\
0 & 0 & 2.8449 & 0
\end{pmatrix}
\]
4.3 Lab Testing

Further lab testing was conducted with the grooming tool using the test tank and measuring the power and velocity of the CrustCrawler 600 motor running on an IS900 silicone fouling release coating. This data was also compared to the field data to determine if the biological fouling influenced the motor’s power usage. The angular velocity of the five different CrustCrawler 600 motors in Figure 54 show a relatively constant speed throughout the test.

\[
\begin{pmatrix}
46.3059 & 21.9959 & 0 \\
5.3575 & -5.4215 & 0 \\
0 & 0 & 8.0057 \\
0 & 0 & 0
\end{pmatrix}
\] (21)

\[
\begin{pmatrix}
5.7636 & 0 & 0 & 0 \\
0 & -24.7470 & 0 & 0 \\
240.7608 & -3.4842 & 0 & 0 \\
0 & 0 & 8.3091 & 0 \\
0 & 0 & 0 & 2.8449
\end{pmatrix}
\] (22)

Figure 54: Lab Test Tank CrustCrawler 600 Motor Angular Velocity
4.4 Field Testing

4.4.1 Grooming Power and Angular Velocity

After testing in the lab, it was necessary to bring the entire grooming vehicle to Port Canaveral for field testing of the system. The grooming tests were completed using the CrustCrawler 600 motors. The tests were completed by running the system two lengths of submerged plate and comparing the results. The other portion of this test was to determine the grooming effectiveness by comparing the biological fouling on the submerged plate before and after each grooming pass. The test also gave a good idea of the power requirements of the system using the data logger that was built into the CrustCrawler 600 BLDC motor controller. The BLDC motor controllers worked using an open loop current control platform which did not allow for control of the shaft speed. Instead the throttle position is used as the fixed control which sets a constant power. Therefore, the results obtained from the test allowed for approximate power requirements at different throttle positions with a varying shaft speed. The power requirements were also determined using different combinations of brush rotation direction that are listed in Table 7 and the brush locations are in Figure 55.
The testing of the grooming tool in a field environment allowed for a better understanding of the behavior of the grooming system in terms of drivability and grooming effectiveness. The different combinations of rotation direction also gave insight into power requirements to determine if a combination improved the overall system efficiency. The power usage from this test in Figure 56 shows the most efficient setting is all motors rotating in the clockwise (CW) direction.
The field tests also showed the behavior of an open loop constant power BLDC motor controller. Figure 56 shows a relatively constant power signal. Figure 57 shows the angular velocity of each motor and how it varies greatly throughout the test. This is primarily caused by the open loop controller that is not designed to hold a fixed speed. The large variations were produced by the movement of the brushes across different levels of biological fouling.
A comparison can be found between the lab testing angular velocity in Figure 54 and the field testing angular velocity in Figure 57. The lab testing was conducted with the grooming brush stationary on a silicone fouling release coating and the field testing was done in a more dynamic moving environment on the same silicone fouling release coating. In the lab environment, there is only a minor amount of change in the motor speed. The same cannot be said for the field environment at Port Canaveral where there are extremely large variations in the motor speed. However, at the field test a change in motor behavior occurs near the 1000 second point of the test. This is the point when the entire plate was cleaned from the grooming process. The remainder of the data in Figure 57 past 1000 seconds is the grooming tool running on a groomed surface and the variations in motor speed greatly diminish proving the fact that the level of fouling can be understood by the measurements of the motor.
4.4.2 Suction Force and Grooming Effectiveness

A visual analysis of the test plates at Port Canaveral were conducted to determine the grooming effectiveness. Photos were taken before and after a single pass of the grooming tool moving across the plate at 0.5 m/s. This linear velocity is the specified velocity for the grooming of an Arleigh Burke-class destroyer (Tribou, 2015). The fouling on the plate before the test in Figure 58 shows a consistent level of soft fouling without any hard fouling. After a single pass of the grooming tool in Figure 59 there is a clear indication of the grooming effectiveness. When comparing the before and after image 95% of the surface was successfully groomed. The portion of fouling that remains is known as a tenacious biofouling and research is currently being conducted to understand if this fouling is detrimental to hydrodynamic performance of the ship hull (Gardner & Swain, 2015). From the images, it can be concluded that a suction grooming brush is capable of tool attachment force effective grooming of biological growth.

Figure 58: Soft Fouling on the Submerged Test Plate Before Grooming
4.5 System Reliability

4.5.1 Failure Modes Effects and Criticality Analysis (FMECA)

The completion of the FMECA (Appendix A) gave insight into the failure modes that could cause a loss of mission or loss of system. The criticality analysis portion of the FMECA allowed for the calculation of the probability of failure and severity of each failure mode. The first row of each table shows the first design with single seals at all interfaces and the second row shows the modified design with two O-rings at each interface. Table 8 shows the totals for the probability of failure of each failure mode in the FMECA.

Figure 59: Submerged Test Plate After Single Pass of the Grooming Tool
Table 8: FMECA Grooming System Probability of Failure

<table>
<thead>
<tr>
<th>Grooming System</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>0</td>
<td>0</td>
<td>3</td>
<td>23</td>
<td>0</td>
</tr>
<tr>
<td>Modified</td>
<td>0</td>
<td>0</td>
<td>6</td>
<td>23</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 8 shows that all the probabilities of failure for both system designs are in Category C and Category D. The three seals that were added to the system are in Category C for redundancy of each interface.

Table 9: FMECA Grooming System Severity

<table>
<thead>
<tr>
<th>Grooming System</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial</td>
<td>11</td>
<td>9</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Modified</td>
<td>8</td>
<td>9</td>
<td>4</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 9 shows the totals for the severity of each failure mode in the FMECA. The initial design using a single seal at each interface produced 20 failure modes that would cause a mission failure. With the addition of the three seals for the modified design the number of failure modes to cause a mission failure decreased to 17.

To better understand the impact of the additional seals a risk assessment matrix was generated. The probability of failure and severity of each failure mode was inserted into the risk assessment matrix. The risk assessment matrix for the initial design in Figure 60 shows that three failure modes are in the red. This was unacceptable and a cause for a design change to reduce the severity if a failure did occur.
The risk assessment matrix in Figure 61 shows that the three additional seals added moved the failure modes to Probability “C” and Severity “IV”. This is improved from the original three failure modes that were ranked as Severity “I”. For the final design 17 of the failure modes are a moderate risk showing that these failure modes should be documented and approved before finalizing the design (Department of Defense, 2012). The other 12 failure modes are in the green meaning that no special attention is required.
4.5.2 Pareto Analysis

Further analysis was completed using a Pareto chart with the assistance of the FMECA to understand key components that are responsible for the majority of the failure rate of the system. This Pareto chart of the initial design in Figure 62 shows that three components are responsible for approximately 82% of the total failure rate of the system. This directly follows the Pareto Principle and displays that the two O-rings for the top and bottom cap and shaft seal will be the primary component to cause system failures. The FMECA also determined that a failure of these three components would also cause a mission failure.
With the additional three seals at each interface a new Pareto chart was generated in Figure 63. The same Pareto Principle still exists and now the six seals account for 90% of the total failure rate. Therefore, only an additional 8% of the total failure rate was included in the seals while spreading the failure rate across the additional three redundant seals.
4.5.3 Reliability Block Diagram

The reliability block diagram (Appendix B) assisted the calculation of the MTBCF due to the integration of parallel redundant systems used for the three sets of seals on the final design. The final system reliabilities in Table 10 show the importance of the redundant systems when comparing the MTBF and MTBCF.

![Figure 63: Final Grooming System Design Pareto Chart](image)

<table>
<thead>
<tr>
<th>Table 10: Comparison Between MTBF and MTBCF</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Time</strong></td>
</tr>
<tr>
<td>Hours</td>
</tr>
<tr>
<td>Mission</td>
</tr>
</tbody>
</table>
These results clearly show that the addition of the extra seal on the covers and output shaft provided more than a one order of magnitude increase in the mission success rate.

4.6 Final Motor Design

After the completion of the research and testing a final design was selected. The final design included the motor and gearbox, underwater housing, motor controller and data logging system. All the individual systems were designed to ensure that all requirements were met.

4.6.1 Motor and Gearbox

After all the tests of the individual brushes, system identification tests and field testing of the grooming systems, a set of parameters were determined for the selection of the final design. From the individual brush testing the brushes become less efficient after 700 RPM therefore a maximum RPM was set at 750 RPM and the torque requirement was set to be no lower than 1.5 N-m. Maxon Precision Motors, Inc. was chosen as the supplier for the motor and gearbox due to the past successful grooming platform application. A 90mm flat BLDC motor with hall effect position sensors was chosen to be mated with a 4.3:1 gearbox. This combination meets or exceeds all requirements (Table 11) that were set during the testing and research phase.
Table 11: Drivetrain Requirements and Final Drivetrain Design Parameters

<table>
<thead>
<tr>
<th>Specification</th>
<th>Design Requirements</th>
<th>Final Design Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous Output Speed (RPM)</td>
<td>750</td>
<td>748</td>
</tr>
<tr>
<td>Continuous Output Torque (N-m)</td>
<td>1.5</td>
<td>1.73</td>
</tr>
<tr>
<td>Max Input Voltage (V)</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>Max Power (W)</td>
<td>166</td>
<td>145</td>
</tr>
<tr>
<td>Position Control Sensors</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

4.6.2 Motor Control and Data Logging

The final grooming tool powertrain was designed to rotate at a specified RPM throughout different load conditions that will vary during the grooming process for different types and amounts of surface fouling. The speed of the grooming brush was designed to be controlled from the surface and the actual speed and motor parameters are sent to the surface and displayed on a digital readout while also being logged to a data file. Therefore, it was necessary that the final BLDC motor controller is capable of closed-loop control, ability to send and receive digital and analog control signals and function in an oil filled environment. Maxon Precision Motors, Inc. develops a range of products designed for simple interface between the Maxon BLDC motor and a surface microcontroller (Figure 64). The final motor controller chosen was a small four-quadrant controller capable of fixed speed closed-loop control. The BLDC controller had the required input and outputs for total control and data logging capabilities for the grooming system.
The data is sent from the surface controls down to the motor controller via a subsea tether with ten conductors. The digital inputs are set high with a 5V signal and the analog inputs are 12-bit with a -10V to +10V differential. The digital outputs are also set high with a 5V signal and the analog outputs are 12-bit with a -4V to +4V differential. The first digital input is used to turn the motor on or off and the second digital input is used to set the direction of the motor rotation. The digital output pins were not used for this final design; however, they could be used for speed or current comparators if needed for future applications. The first analog input was used to control the speed using a 0 – 5KΩ potentiometer and the second analog input was not used. In the future, this other input could be used to set the acceleration and deceleration rates. The first analog output was used to measure the speed of the motor shaft and the second output was used to measure the motor current for power calculations. Table 12 shows the conductor usage for the tether and the single conductor available for future expansion.
<table>
<thead>
<tr>
<th>Conductor #</th>
<th>Wire Gauge</th>
<th>Purpose</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24</td>
<td>Analog Out – Motor Speed</td>
</tr>
<tr>
<td>2</td>
<td>24</td>
<td>Analog Out – Motor Current</td>
</tr>
<tr>
<td>3</td>
<td>20</td>
<td>Power – Positive</td>
</tr>
<tr>
<td>4</td>
<td>20</td>
<td>Power – Positive</td>
</tr>
<tr>
<td>5</td>
<td>28</td>
<td>Analog Input – Speed Control Potentiometer</td>
</tr>
<tr>
<td>6</td>
<td>20</td>
<td>Power – Negative</td>
</tr>
<tr>
<td>7</td>
<td>20</td>
<td>Power – Negative</td>
</tr>
<tr>
<td>8</td>
<td>28</td>
<td>Digital Input – System Enable</td>
</tr>
<tr>
<td>9</td>
<td>28</td>
<td>Digital Input – Motor Direction</td>
</tr>
<tr>
<td>10</td>
<td>28</td>
<td>Open for Further Expansion</td>
</tr>
</tbody>
</table>

A motherboard was designed and built to support the BLDC motor controller and allowed for easy connection of the Input/Output (I/O) signals. The motherboard was designed with two systems to condition the incoming voltage supply and voltage signals to each motor winding. The incoming voltage supply had reverse polarity diode protection, current protection fuse, a capacitor to smooth the ripple in the voltage supply (Figure 65). The voltage to each motor winding was conditioned using capacitors, a resistor and a motor choke to reduce Electromagnetic Interference (EMI) (Figure 66). The values of these components were specified by Maxon to ensure proper function of the BLDC motor controller.
The surface control box contains the physical switch inputs required for motor control as well as the microcontroller used to create a digital readout of the real-time motor conditions and log motor data to a removable Secure Digital (SD) card for post mission data analysis. The final box design incorporated three toggle switches and one rotary potentiometer. The first switch is used to enable the motor controller, the second switch controlled the direction of motor rotation and the third switch controlled when the data logging starts and ends. The rotary potentiometer is used to vary the voltage signal to the motor controller to control the speed of the motor. The real-time information is displayed on a 4x20 Liquid Crystal Display.
(LCD) screen to enable the operator to know how the system is functioning during the mission (Figure 67).

Figure 67: Surface Control Box with Digital Readout and Data Logger

The microcontroller used for the final design is an Arduino Pro Mini which was chosen because of the small size and ease of programming and accessibility. The microcontroller reads the digital and analog inputs from the surface switches and the information from the motor controller. It also interfaces with the 4x20 LCD screen, microSD card reader, Real Time Clock (RTC) module and multiple Light Emitting Diode (LED) lights used for system status. The LCD screen was controlled using a Transistor-Transistor Logic (TTL) serial backpack to simplify control, as well as, reduce the number of I/O pins used on the microcontroller. The microSD card reader used the Inter-Integrated Circuit (I2C) interface to enable the data to be logged into a text file for post mission data analysis. The RTC module
also uses the I2C interface and allows for time stamps to be added to each data entry. The RTC module was fitted with a backup battery to ensure that the time is always correct when the system power is shutoff. The final interface with the microcontroller are the LED status lights. The four lights are used to indicate when the system is armed, when data is being logged and when the motor is spinning clockwise or counterclockwise. The entire system is powered by the same 24V DC power source as the motor and the voltage is stepped down using a standard 5V voltage regulator. The decreased voltage transferred large amounts of heat energy to the voltage regulator. The voltage regulator was outfitted with an aluminum fin heatsink and fan for added convective heat transfer to decrease the temperature of the regulator. The overall control system is compact and portable for easy use during field deployments.

4.6.3 Underwater Housing

To ensure the protection of the motor, gearbox and motor controller it was necessary to design and build a waterproof housing (Figure 68). The final design utilized an oil filled housing instead of an airtight housing due to the simpler sealing techniques to prevent salt water intrusion. The oil also acts as a heat transfer agent to prevent the BLDC motor and motor controller from overheating during grooming operations. The oil used for the final design is mineral oil because it would not have a negative environmental impact if a leak were to occur. The design of the housing is a cylinder with two endcaps that each incorporate a double seal for redundant prevention of salt water intrusion. The housing is made of all aluminum due to its lightweight, ease of machining and high heat transfer coefficient.
The top cap of the housing is the threshold for the control tether, location of the oil fill port and the support for the motor controller. This cap is the first component to be removed when any work or service is conducted on the grooming motor. The cap is bolted to the bottom cap of the housing to prevent either cap from separating from the housing. The bottom cap supports the motor and gearbox as well as supporting the bearing and dual shaft seals (Figure 69). The bearing material used for the final design is full ceramic Zirconium Dioxide (ZrO2) due to the ability to withstand high temperatures at high speeds and high resistance to corrosion. The incorporation of an oil filled housing allowed for the use of lower cost seals due to smaller pressure differences between the inside of the housing and the outside environment. It was also important to ensure that the final seal was able to
withstanding the high output shaft speeds and saltwater environment. The final bearing is rated to a 10psi pressure differential and 1000 FPM and out final design is running at 100 FPM and near 1 psi. The seals will also be greased to ensure protection from wear on the shaft causing premature seal or shaft damage resulting in leakage.

![Figure 69: Output Shaft Bearing Support and Dual Seal Design](image)

One of the challenges of the design of the powertrain and waterproof housing was to use as many Commercial Off The Shelf (COTS) components as possible to keep costs low and ensure a high material availability. The Maxon gearbox did not come
standard with an output shaft long enough for the proper function and a custom modification would have pushed costs five times higher and lengthened the manufacturing time by six months. A design modification was completed with the addition of a custom manufactured output shaft that would attach to the gearbox to lengthen the output shaft for proper function. The cost of the custom shaft would be much lower than changing the gearbox and allow for more material choices and design flexibility.
Chapter 5 – Conclusions

This research has determined that the grooming tool design developed here provides a system that has the potential to become a fully functioning tool for the Navy fleet. The new brush design demonstrated that the reduction of suction force is related to the decrease in brush torque. The suction force was decreased by allowing for fluid transfer through the brush tufts while still attaining brush efficiency by limiting the number of tufts in contact with the grooming surface. The construction of a functional five headed grooming test bed allowed for the field testing of the suction brush on test fouled submerged test plates in Port Canaveral. It was determined through visual analysis that the suction brushes were capable of attachment force and effective grooming of soft biological fouling. System Identification testing in the lab allowed for a better understanding of the grooming process by looking at the different variables that determine a model of the BLDC motor under different loads. A comparison of the torque measurements between a brush in air and a brush in water showed the effects of the hydrodynamic forces on the grooming brush. With an understanding of this information a comparison test was conducted between the grooming system in the lab and in the field on silicone fouling release coating. These tests showed that the BLDC motor power measurements are related to the level of biological fouling. During the design process a reliability analysis was completed and it was determined that the inclusion of three components improved the MTBCF by more than a factor of ten. It was also determined that the inclusion of a Pareto Analysis in the design phase instead of the sustainment phase had a positive impact on the overall design. The three new seals to create redundant double seals increased the system critical reliability from 814 hours to 9,030 hours. The system also incorporated a portable control box to control the grooming system and collect and store the motor data.
from the grooming missions. The final design incorporated detailed research about each portion of grooming system to create the ideal system for prevention of biofouling on a ship hull.

In conclusion, the hypotheses developed to guide this research were answered as follows.

- The reduction in brush torque was found to be related to the attachment force of the brush.
- The grooming brush design was found to provide the attachment forces and grooming capabilities to maintain the surface free of fouling.
- The power requirements of the grooming powertrain were found to be related to the level of biological fouling when comparing a clean plate to a plate with biological fouling.
- The Mean Time Between Critical Failure (MTBCF) of a grooming system was found to be able to be improved by a factor of ten with the inclusion of no more than five components with the use of Pareto analysis.
Chapter 6 – Recommendations

6.1 – Hydrodynamics

The hydrodynamic behavior of a grooming brush should be tested and analyzed using a Laser Doppler Velocimeter (LDV) to confirm the results of the literature review. A better understanding of the fluid flow will allow for a better refined grooming brush.

- Allow for the beginning of a Computational Fluid Dynamic (CFD) model
  - This model can be improved using empirical test results from the lab test tank
  - This model will allow for testing of more brush designs at a faster rate
- Extension of the system Identification with a focus on torque requirements
  - Determine the torque requirements of different grooming brushes and use this information to help understand the brush’s drag

6.2 – Grooming System Design

The grooming system was designed to create a solution using COTS components with easily accessible materials. With more time, better materials could be used to improve the final design.

- The output shaft material should be better suited for high wear due to the seal interface
  - Consider having the final shaft Chrome or Nickel plated and hardened
- The controller could be improved for better control and accuracy
- Determine the frequency to eliminate and design an RC filter for data signal processing
- Place another microcontroller in the housing to allow for serial communication and to allow for a functioning system with few electrical connections
- Create a ground fault monitoring system for field use to create a safer system
  - Expand the system from one brush to a full system of brushes similar to the test platform

6.3 – Reliability Analysis

Most of the component reliability predictions were determined from NPRD and not directly from the supplier. More communication with the components suppliers can allow for better predictions to be obtained.

- Create a set of reliability metrics for the system to meet before conducting a reliability analysis
- Determine mitigation methods to eliminate some of the risks located in the moderate areas of the risk assessment matrix
- Conduct the similar Pareto analysis with the failure data once the system is fielded to verify the effectiveness of this analysis method in the design phase
References


## Appendix A – FMECA Worksheet

The first portion if the Failure Modes and Effects (FMEA)

<table>
<thead>
<tr>
<th>ID #</th>
<th>Part Name</th>
<th>Function Number</th>
<th>Function Description</th>
<th>Failure Mode</th>
<th>Functional Failure Description</th>
<th>Failure Mode &amp; Causes</th>
<th>Local Effects</th>
<th>Next Higher Effect</th>
<th>Compensating Provisions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Power and Controls wet mate connector</td>
<td>1</td>
<td>Provide for a waterproof electrical interface between the control tether and motor controller</td>
<td>Connecto r begins to leak</td>
<td>FOD</td>
<td>Salt water intrusion</td>
<td>saltwater and oil emulsion</td>
<td>Degraded Function</td>
<td>None</td>
</tr>
<tr>
<td>1</td>
<td>Power and Controls wet mate connector</td>
<td>1</td>
<td>Provide for a waterproof electrical interface between the control tether and motor controller</td>
<td>Connecto r does not allow for proper electrical flow between housing and tether</td>
<td>Corrosion, FOD</td>
<td>Electrical signals cannot pass through the connector</td>
<td>Internal components do not receive electrical power or control signals</td>
<td>Abort</td>
<td>None</td>
</tr>
<tr>
<td>2</td>
<td>Housing upper cap</td>
<td>1</td>
<td>Enclose the top portion of the housing. Also, provide for a structural mount for the motor controller and wet mate connector</td>
<td>Fails to support the wet mate connector or motor controller</td>
<td>Corrosion, FOD, Fracture</td>
<td>Wet mate connector or motor controller no longer supported</td>
<td>Salt water intrusion through connect or interface</td>
<td>Possible Loss of Unit</td>
<td>None</td>
</tr>
<tr>
<td></td>
<td>Housing upper cap</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td>Salt water contact with electrical components</td>
<td>Loss of Unit</td>
<td>None</td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>------------------</td>
<td>---</td>
<td>----------</td>
<td>----------</td>
<td>----------</td>
<td>-----------------------------------------------</td>
<td>--------------</td>
<td>------</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Housing upper cap o-ring upper</td>
<td>1</td>
<td>Enclose the top portion of the housing. Also, provide for a structural mount for the motor controller and wet mate connector</td>
<td>B</td>
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<td>Creates a seal between the housing upper cap and the housing body to prevent water intrusion</td>
<td>A</td>
<td>Fails to prevent water intrusion</td>
<td>Wear</td>
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<td>Wear</td>
<td>Oil leakag e</td>
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<td>Fails to support the upper and lower caps</td>
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<td>Loss of support</td>
<td>Motor controller and gearbox no longer supported</td>
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<td>Corrosion, FOD, Fracture</td>
<td>Salt water intrusion</td>
<td>Salt water contact with motor and electrical components</td>
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<td>Convert electrical energy to rotational torque to drive the reduction gearbox</td>
<td>A</td>
<td>Fails to rotate</td>
<td>Short circuit, seized</td>
<td>No output torque to the gearbox</td>
<td>Gearbox output shaft unable to rotate</td>
<td>Abort</td>
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<td>BLD Motor</td>
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<td>Convert electrical energy to rotational torque to drive the reduction gearbox</td>
<td>B</td>
<td>Does not rotate and the correct velocity</td>
<td>Open circuit, wear</td>
<td>Incorrect shaft output into gearbox</td>
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<td>Amplify the input torque from the BLDC motor to the output shaft</td>
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<td>Fails to provide an output torque</td>
<td>Seized, fractured</td>
<td>Gearbox input shaft unable to rotate</td>
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<td>Amplify the input torque from the BLDC motor to the output</td>
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<td>Provides degraded torque output</td>
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<td>Inadequate torque transferred to the output</td>
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<td>Provide support to the reduction gearbox and BLDC motor</td>
<td>Fails to support the reduction gearbox</td>
<td>Fracture, Loss of support</td>
<td>Abort, None</td>
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<td>Transmit rotational torque from the reduction gearbox to the grooming brush</td>
<td>Fails to transmit torque</td>
<td>Fracture, Corrosion, Rotational torque not transferred to grooming brush</td>
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<td>Provide an interface for the output shaft seals to prevent water intrusion</td>
<td>Fails to provide a water proof interface</td>
<td>Wear, Fracture, Corrosion, Surface damage prevents adequate seal</td>
<td>Degraded Function, None</td>
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<td>Excess strain on the output seals and gearbox</td>
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<td>Fails to provide structural support to the delrin spacer</td>
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<td>Failure to provide structural support</td>
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<td>Corrosion, Fracture</td>
<td>Fails to support seals and bearings</td>
<td>Salt water intrusion causing damage to internal components</td>
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<td>Fails to prevent oil leakage</td>
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<td>Fails to provide a connection between the output shaft and grooming brush</td>
<td>Wear, Fracture</td>
<td>Fails to support and transfer torque</td>
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<td>Convert the electrical power and input signals from the surface into a waveform to power the BLDC motor at a desired speed</td>
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<td>Fails to provide waveform to rotate the motor</td>
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<td>No output power provided to BLDC motor</td>
<td>BLDC motor unable to provide torque to grooming brush</td>
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<td>Convert the electrical power and input signals from the surface into a waveform to power the BLDC motor at a desired speed</td>
<td>B</td>
<td>Provides erroneous waveform to rotate the motor</td>
<td>Short circuit, Open circuit</td>
<td>False output power provided to BLDC motor</td>
<td>BLDC motor does not rotate at the correct speed</td>
<td>Degrade function</td>
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<td>17 Motor controller</td>
<td>2</td>
<td>Provide motor parameter data to the surface</td>
<td>A</td>
<td>Fails to provide motor data</td>
<td>Open circuit</td>
<td>No data provided to data readout or collection system</td>
<td>Unable to know the exact behavior of the grooming system or analyze data after use</td>
<td>Degrade function</td>
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The final portion of the FMECA is the criticality and failure rate information.

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<th>Failure Mode Ratio</th>
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<p>|   | 0.33             | 3.064                          | 1.0213                        | 23             | 2.35E-05       | D              |
|   | 1.00             | 200                            | 200                           | 23             | 4.59E-03       | C              |
|   | 1.00             | 200                            | 200                           | 23             | 4.59E-03       | C              |
|   | 1.00             | 27.983                         | 27.983                        | 23             | 6.43E-04       | D              |
|   | 0.25             | 25.089                         | 6.2723                        | 23             | 1.44E-04       | D              |
|   | 0.25             | 25.089                         | 6.2723                        | 23             | 1.44E-04       | D              |</p>
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Appendix B – Reliability Block Diagram
Appendix C – Field Test MATLAB Code

% Port Test
% 8/27/2015
% First test with wheels

clear all, close all, clc

data1=xlsread('data.csv','A1:E2647');
data2=xlsread('data.csv','F1:J2545');
data3=xlsread('data.csv','K1:O2771');
data4=xlsread('data.csv','P1:T2343');
data5=xlsread('data.csv','U1:Y2858');

throttle1=data1(:,1); volt1=data1(:,2); current1=data1(:,3); rpm1=data1(:,5);
power1=volt1.*current1;

throttle2=data2(:,1); volt2=data2(:,2); current2=data2(:,3); rpm2=data2(:,5);
power2=volt2.*current2;

throttle3=data3(:,1); volt3=data3(:,2); current3=data3(:,3); rpm3=data3(:,5);
power3=volt3.*current3;

throttle4=data4(:,1); volt4=data4(:,2); current4=data4(:,3); rpm4=data4(:,5);
power4=volt4.*current4;

throttle5=data5(:,1); volt5=data5(:,2);
current5=data5(:,3);
rpm5=data5(:,5);
power5=volt5.*current5;

subplot(211)
plot(rpm1)
subplot(212)
plot(throttle1)

power=power1(1:1900)+power2(1:1900)+power3(1:1900)+power4(1:1900)+power5(1:1900);

figure(2)
plot(power)

figure(3)
plot(throttle1(1:1900), 'LineWidth', 2)
hold on
plot(throttle2(1:1900), 'LineWidth', 2)
plot(throttle3(1:1900), 'LineWidth', 2)
plot(throttle4(1:1900), 'LineWidth', 2)
plot(throttle5(1:1900), 'LineWidth', 2)
legend('motor1', 'motor2', 'motor3', 'motor4', 'motor5')
hold off

figure(4)
plot(rpm1(1:1900), 'LineWidth', 2)
hold on
plot(rpm2(1:1900), 'LineWidth', 2)
plot(rpm3(1:1900), 'LineWidth', 2)
plot(rpm4(1:1900), 'LineWidth', 2)
plot(rpm5(1:1900), 'LineWidth', 2)
legend('motor1', 'motor2', 'motor3', 'motor4', 'motor5')
title('Field Test - CrustCrawler Motor Shaft Speed')
xlabel('Time (sec)')
ylabel('Angular Velocity (RPM)')
hold off
set(gca, 'FontSize', 22, 'LineWidth', 2)

figure(5)
plot(power1(1:1900), 'LineWidth', 2)
hold on
plot(power2(1:1900),'LineWidth',2)
plot(power3(1:1900),'LineWidth',2)
plot(power4(1:1900),'LineWidth',2)
plot(power5(1:1900),'LineWidth',2)
plot(power,'LineWidth',2)
legend('motor1','motor2','motor3','motor4','motor5','Total Power')
title('Field Test - CrustCrawler Motor Power')
xlabel('Time (sec)')
ylabel('Power (Watt)')
text(300,600,'1','FontSize',28)
text(750,600,'2','FontSize',28)
text(1200,600,'3','FontSize',28)
text(1700,600,'4','FontSize',28)
hold off
set(gca,'FontSize',22,'LineWidth',2)
Appendix D – System Identification MATLAB Code

% Epoxy Plate Compressed in Air

close all

load data.mat;
load data2.mat;

\( t = (1/10000):(1/10000):15; \)
\( Ts = 1/10000; \)
torque = data(:,1);
Torque = data2(:,1);
encoder = (104.03.*data(:,2)).*(2*pi()/60);
curwhite = ((3.4461.*data(:,3)) + 0.0212);
curblack = ((5.4945.*data(:,4)) + 0.0431);
curgreen = (5.0033.*data(:,5));

voltwhite = (4.2573.*data(:,6));
voltblack = (4.179.*data(:,7));
voltgreen = (3.9313.*data(:,8));

curwhite = idfilt(curwhite, 5, 0.1);
curblack = idfilt(curblack, 5, 0.1);
curgreen = idfilt(curgreen, 5, 0.1);
voltwhite = idfilt(voltwhite, 5, 0.1);
voltblack = idfilt(voltblack, 5, 0.1);
voltgreen = idfilt(voltgreen, 5, 0.1);

encoder = idfilt(encoder, 5, 0.01);

% Derivative to determine velocity
for \( i = 2:length(encoder) \)
    theta(i) = (t(i) - t(i-1)) * (encoder(i-1) + ((encoder(i) - encoder(i-1))/2));
end

theta = cumsum(theta);

% Phase shift equation required for 3-Phase BLDC Motor
shift = zeros(1, 23);
trapforma=trapezoid(3.*theta);
trapformb=[trapforma(1:149977),shift];
trapformc=[trapforma(1:149954),shift,shift];

% Take a Derivative of the position twice to get acceleration
for i=2:(length(encoder)),
    thetadotdot(i)=(encoder(i)-encoder(i-1))/2/Ts;
end;

Kf=1.38*10^-8;
J=.03;

TETL=(Kf.*encoder)+(J.*thetadotdot');

% Filter the Torque data for use in the model
torquefilt=-1.*(idfilt(torque,5,.002));
Torquefilt=-1.*(idfilt(Torque,5,.002));

for i=2:(length(data)),
    Dia(i)=(curwhite(i)-curwhite(i-1))/2/Ts;
end;

for i=2:(length(data)),
    Dib(i)=(curblack(i)-curblack(i-1))/2/Ts;
end;

L=.005;
Ra=.3;
Rb=.4;

Ke=.578;
Kt=Ke/.00684;

emfa=(Ke/2).*encoder.*trapforma';
emfb=(Ke/2).*encoder.*trapformb';
emfc=(Ke/2).*encoder.*trapformc';

Vab=(Ra-Rb)+(L.*(Dia'-Dib'))+emfa-emfb;
Vbc=(Ra+(2.*Rb))+(L.*(Dia'+(2.*Dib')))+emfb-emfc;
\[ Te = (K_t/2) \times ((\text{trapform}_a \times \text{curwhite}) + (\text{trapform}_b \times \text{curblack}) + (\text{trapform}_c \times \text{curgreen})) \]

\[
\text{Tefilt} = \text{idfilt}(Te, 5, .002);
\]

\[
\text{Dt} = Te - \text{torquefilt};
\]

\[
\text{emfab} = \text{emfa} - \text{emfb};
\]

\[
\text{emfbc} = \text{emfb} - \text{emfc};
\]

\[
\text{input} = [\text{(Vab-emfab)}, (\text{Vbc-emfbc}), \text{TETL}] ;
\]

\[
\text{output} = \text{[curwhite, curblack, curgreen, encoder, theta']};
\]

\[
\text{datasolve} = [\text{output, input}];
\]

\[
\text{datafit} = \text{datasolve}(10000:74000, :);
\]

\[
\text{dataval} = \text{datasolve}(74001:140000, :);
\]

\[
\text{fitoutput} = \text{datafit}(:, 1:5);
\]

\[
\text{fitinput} = \text{datafit}(:, 6:8);
\]

\[
\text{valoutput} = \text{dataval}(:, 1:5);
\]

\[
\text{valinput} = \text{dataval}(:, 6:8);
\]

% Split the data in half for fit and validation

\[
\text{fitdata} = \text{iddata(fitoutput, fitinput, Ts)};
\]

\[
\text{valdata} = \text{iddata(valoutput, valinput, Ts)};
\]

% Initial guess for the parameters

\[
A = \begin{bmatrix}
-20.6644 & 0 & 0 & 0 & 0 \\
-16.6504 & 0 & 0 & 0 & -0.0029 \\
6.3744 & 0 
\end{bmatrix};
\]

\[
B = \begin{bmatrix}
55.2256 & -12.4941 & 0 \\
-9.2185 & 2.1556 & 0 \\
9.0664 & 0 & 0 \\
0 & 0 & 9.0664 \\
0 & 0 & 0 
\end{bmatrix};
\]

\[
C = \begin{bmatrix}
1.1748 & 0 & 0 & 0 & 0 \\
-11.2180 & 0 & 0 & 0.9816 & -7.8896 \\
0 & 0 & 0 & 6.3744 \\
7.2925 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 6.3744 
\end{bmatrix};
\]

\[
D = \text{zeros}(5, 3);
\]

% NaN variables for the PEM model to solve for

\[
As = \begin{bmatrix}
\text{NaN} & 0 & 0 & 0 & 0 \\
\text{NaN} & 0 & 0 & 0 & 0 \\
\text{NaN} & 0 & 0 & 0 & 0 \\
\end{bmatrix};
\]

\[
Bs = \begin{bmatrix}
\text{NaN} & \text{NaN} & 0 & 0 & 0 \\
\text{NaN} & \text{NaN} & 0 & 0 & 0 \\
\text{NaN} & 0 & 0 & 0 & 0 \\
\end{bmatrix};
\]

% NaN variables for the PEM model to solve for

\[
As = \begin{bmatrix}
\text{NaN} & 0 & 0 & 0 & 0 \\
\text{NaN} & 0 & 0 & 0 & 0 \\
\text{NaN} & 0 & 0 & 0 & 0 \\
\end{bmatrix};
\]

\[
Bs = \begin{bmatrix}
\text{NaN} & \text{NaN} & 0 & 0 & 0 \\
\text{NaN} & \text{NaN} & 0 & 0 & 0 \\
\text{NaN} & 0 & 0 & 0 & 0 \\
\end{bmatrix};
\]
Cs=[NaN 0 0 0; NaN 0 0; NaN NaN 0 0; 0 0 NaN 0; 0 0 0 NaN];
Ds=zeros(5,3);
x0s=[0;0;0;0];
Ks=zeros(4,5);
m3=idss(A,B,C,D,K,x0,Ts);
setstruc(m3,As Bs Cs Ds Ks x0s);
set(m3, 'Ts', 0);

m4=pem(fitdata,m3); % PEM Function to solve model

t = 0:Ts:Ts*(length(fitdata.y)-1);
ysim4=sim(m4, iddata([], fitdata.u, Ts));

%% Data Fit Plots
figure(1)
subplot(311);
plot(t, ysim4.y(:,1), 'r', t, fitdata.y(:,1), 'c', 'LineWidth', 2);
hold on
title('Compressed Epoxy Plate in Air Current Fit Data')
extend('Simulation', 'Test Fit Data')
ylabel('Current (Amps)')
xlim([0 8])
hold off
set(gca, 'LineWidth', 2, 'FontSize', 22)
subplot(312);
plot(t, ysim4.y(:,2), 'r', t, fitdata.y(:,2), 'c', 'LineWidth', 2);
hold on
legend('Simulation', 'Test Fit Data')
ylabel('Current (Amps)')
xlim([0 8])
hold off
set(gca, 'LineWidth', 2, 'FontSize', 22)
subplot(313);
plot(t, ysim4.y(:,3), 'r', t, fitdata.y(:,3), 'c', 'LineWidth', 2);
hold on
legend('Simulation', 'Test Fit Data')
ylabel('Current (Amps)')
xlim([0 8])
hold off
set(gca, 'LineWidth', 2, 'FontSize', 22)
xlabel('Time (sec)')
xlim([0 8])
hold off
set(gca,'LineWidth',2,'FontSize',22)
figure(2)
subplot(211);
plot(t,ysim4.y(:,4),'r',t,fitdata.y(:,4),'c','LineWidth',2);
hold on
title('Compressed Epoxy Plate in Air Velocity and Position Fit Data')
legend('Simulation','Test Fit Data')
ylabel('Velocity (rad/sec)')
xlim([0 8])
hold off
set(gca,'LineWidth',2,'FontSize',22)
subplot(212);
plot(t,ysim4.y(:,5),'r',t,fitdata.y(:,5),'c','LineWidth',2);
hold on
legend('Simulation','Test Fit Data')
ylabel('Position (rad)')
xlabel('Time (sec)')
xlim([0 8])
hold off
set(gca,'LineWidth',2,'FontSize',22)

%% simulate output with validation data set
ysim3 = sim(m4,iddata([],valdata.u,Ts));

t = 0:Ts:Ts*(length(valdata.y)-1);
figure(3)
subplot(311)
plot(t,ysim3.y(:,1),t,valdata.y(:,1),'LineWidth',2);
hold on
title('Compressed Epoxy Plate in Air Current Validation Data')
legend('Simulation','Test Val Data')
ylabel('Current (Amps)')
xlim([0 8])
hold off
set(gca, 'LineWidth',2,'FontSize',22)

subplot(312)
plot(t,ysim3.y(:,2),t,valdata.y(:,2),'LineWidth',2);
hold on
legend('Simulation','Test Val Data')
ylabel('Current (Amps)')
xlim([0 8])
hold off
set(gca, 'LineWidth',2,'FontSize',22)

subplot(313)
plot(t,ysim3.y(:,3),t,valdata.y(:,3),'LineWidth',2);
hold on
legend('Simulation','Test Val Data')
ylabel('Current (Amps)')
xlabel('Time (sec)')
xlim([0 8])
hold off
set(gca, 'LineWidth',2,'FontSize',22)

figure(4)

subplot(211)
plot(t,ysim3.y(:,4)+encoder(74001),t,valdata.y(:,4),'LineWidth',2);
hold on
title('Compressed Epoxy Plate in Air Position and Velocity Validation Data')
legend('Simulation','Test Validation Data','Location','SouthEast')
ylabel('Velocity (rad/sec)')
axis([0 8 -20 60])
hold off
set(gca, 'LineWidth',2,'FontSize',22)

subplot(212)
plot(t,ysim3.y(:,5),t,valdata.y(:,5)-theta(74001),'LineWidth',2);
hold on
legend('Simulation','Test Validation Data','Location','SouthEast')
ylabel('Position (rad)')
xlabel('Time (sec)')
xlim([0 8])
y1=ginput(2);
%% Torque Comparison Plot
figure(5)
plot(torque(10000:150000), 'LineWidth', 3)
hold on
plot(Torque(10000:150000), 'LineWidth', 3, 'Color', [0,1,0, .1])
legend('Air', 'Water')
y=ginput(8);
text(y(1),y(9)-.5, [num2str(y(9)-y(10))], ' N-m (Water)'
     ,'FontSize',22)
text(y(1),y(9)-1, [num2str(y(11)-y(12))], ' N-m (Air)'
     ,'FontSize',22)
text(y(5),y(13)-.5, [num2str(y(13)-y(14))], ' N-m
     (Water)'
     ,'FontSize',22)
text(y(5),y(13)-1, [num2str(y(15)-y(16))], ' N-m
     (Air)'
     ,'FontSize',22)
plot(y(1),y(9), 'mo', 'MarkerSize',10, 'MarkerFaceColor','m')
plot(y(2),y(10), 'mo', 'MarkerSize',10, 'MarkerFaceColor','m')
plot(y(3),y(11), 'mo', 'MarkerSize',10, 'MarkerFaceColor','m')
plot(y(4),y(12), 'mo', 'MarkerSize',10, 'MarkerFaceColor','m')
plot(y(5),y(13), 'mo', 'MarkerSize',10, 'MarkerFaceColor','m')
plot(y(6),y(14), 'mo', 'MarkerSize',10, 'MarkerFaceColor','m')
plot(y(7),y(15), 'mo', 'MarkerSize',10, 'MarkerFaceColor','m')
plot(y(8),y(16), 'mo', 'MarkerSize',10, 'MarkerFaceColor','m')
title('Torque Comparison Between Epoxy Plate in Air Vs. Water')
xlabel('Time (sec)')
ylabel('Torque (N-m)')
hold off
set(gca,'FontSize',22)

% Final Model Matrices
m4.a
m4.b
m4.c
m4.d
Appendix E – Trapezoid Waveform Function

```matlab
function s = trapezoid(t)
% trapezoid(t) creates a time based trapezoid waveform
% For example, generate a 30 Hz square wave:
% t = 0:.0001:.0625;
% y = square(2*pi*30*t);, plot(t,y)

tmp = mod(t+pi/4,2*pi);

a = (tmp < pi/2);
b = (tmp >= pi/2 & tmp < pi);
c = (tmp >= pi & tmp < 3*pi/2);

rise = 2*tmp/pi;
fall = -2*(tmp-pi)/pi+1;
nodd = a.*rise + b + c.*fall;
s = 2*nodd-1;
```
Appendix F – (CAD) Drawings for Housing