Design and evaluation of a magnetically-geared underwater propulsion system for autonomous underwater and surface craft

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***Abstract* - This paper will cover the work performed in the Autonomous Ocean Systems Lab (AOSL) at Memorial University of Newfoundland in the design, construction and evaluation of a high performance under water propulsion system. A small 400W thruster was developed for testing and experimentation while a 3kW thruster was designed specifically for the Sea Dragon, an unmanned surface craft (USC) currently being built by the AOSL.**

Each thruster consists of three main components: a brushless DC motor, a custom propeller, and a magnetic gearing system. A duct was incorporated as a means to improve hydrodynamic performance and to protect the propeller. All subsystems are purpose-built to maximize their efficiency at the desired operational point.

A detailed computer model was developed in MATLAB Simulink in order to predict thruster performance. OpenProp was used to design a number of efficient propellers and were tested using the 400W thruster in an open water flume tank. The propellers did not perform as well as expected so additional experiments were performed in an effort to identify the source of discrepancy. It was determined that propeller surface finish and blade thickness have a significant impact on performance. More importantly it was concluded that the quality of flow in the flume tank was not suitable for accurate testing. Bollard tests may provide more accurate results in the future.

The larger 3kW thruster was designed with a greater focus on efficiency. A parametric study was performed in order to identify an ideal propeller geometry that would suit the needs of the Sea Dragon. A custom DC motor was designed such that its efficiency is maximized in the operating regime of the vessel. Simulated results indicate that the overall efficiency of the unit to be between 0.5 and 0.6 which is very attractive for unmanned, untethered vehicles. The thruster will be tested in a tow tank and then onboard the Sea Dragon.

I. MOTIVATION

When considering the nature of unmanned marine operations, the efficiency and overall reliability of a vehicle's propulsion system is of great importance. The attainable mission length is directly proportional to how efficiently the vehicle can propel itself. The robustness of a vehicle is limited by the reliability of its constituents, so reliable propulsion is critical.

The primary incentive of this research is to develop a reliable and efficient underwater propulsion system. By combining a number of design strategies and novel features, it is possible to develop an underwater thruster which out-performs existing technologies, improving the current abilities of unmanned underwater and surface vehicles. The efficiency and reliability of a thruster can be improved by replacing mechanical gear reduction with a magnetic gearing system. Maximum efficiency is also the result of properly designed propeller and electric motor. With an elegant assembly in a rugged envelope, a very attractive propulsion system can be achieved.

The initial part of the research and experimentation will be completed using a small 400 Watt unit that has been designed and built. This ROV thruster was not designed with any particular application in mind but as to serve as a testing platform and proof of concept of the magnetic gear. General sizing was done based on existing small ROV propulsion systems. The second half of this paper will cover a larger 3000 Watt system being built. The larger thruster has been designed with the intention of being installed on the USC Sea Dragon, a large spar-type surface craft currently being built by the AOSL.

II. MAGNETIC GEAR

The integration of a magnetically-coupled gear reduction is the primary difference between the thruster in question and existing systems. The design of magnetic gearing systems and their advantages has been investigated since 1913[1]. It has been shown that a magnetic gear generates less acoustic noise and vibration than their mechanical counterparts. They experience less friction resulting in reduced wear and improved reliability and efficiency. Finally, in the event that a gear rotor becomes overloaded, the magnetic gear will "ratchet" or slip, providing inherent overload protection [2]. The gear conveniently doubles as a magnetic coupling. A magnetic coupling is typically used in underwater systems as a means of isolating external moving parts from the internal components that are vulnerable to corrosion.

Many configurations of magnetic gears exist, however in this system a radial type gear was designed. A radial type magnetic gear consists of three concentric rings. The inner ring (high speed) is coupled directly to the electric motor output and has alternating permanent magnets directed radially. The outer ring (low speed) is coupled directly to the propeller hub and contains a larger number of magnetic pairs. The gear ratio is equal to the ratio of magnetic pairs. The intermediate ring (stationary) contains a characteristic number of ferritic pole pieces which act to modulate the magnetic fields in order to achieve a flux harmony, allowing the gear to "mesh".

The amount of torque that can be reliably transmitted through a magnetic gear was determined using COMSOL [3], a multi-physics simulation software package. In general, the torque capacity of a magnetic gear is proportional to the effective volume. Other factors such as geometry, magnetic properties of the materials and air gap lengths will have an impact on gear performance. Figure 1 shows the results of a COMSOL simulation used to determine the torque capacity of the magnetic gear in the ROV Thruster. The torque capacity is determined by simulating the case of a stall, where the transmitted torque is maximized right before the gear slips. This is accomplished by holding one rotor stationary and incrementally rotating the other. The results indicate that the gear can provide 0.58 N*m of torque to the propeller before the gear is expected to slip.

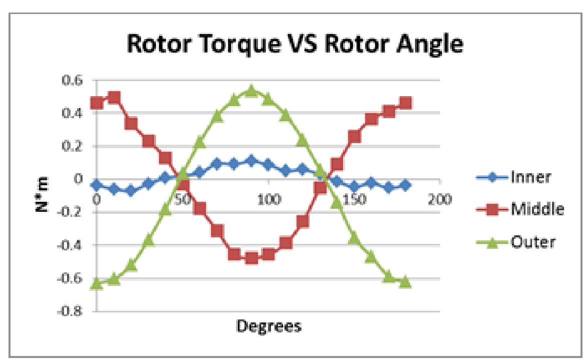

Figure 1 – COMSOL results showing the torque felt by each of the magnetic gear rings as the input rotor is rotated. Output torque peaks at 0.58 Nm.

III. DUCTED PROPELLER

Rather than use existing off-shelf propellers, OpenProp V3.3.4 was used to generate propeller geometries and performance curves. OpenProp [5] is an open-source MATLAB [4] software package used to design and optimize propellers and turbines. The geometry of each propeller is generated such that its efficiency is maximized at the desired operating point. OpenProp also has the capability to optimize a specific propeller for use with a duct.

A shroud with a foil cross section, known as a duct or nozzle, can provide a performance boost to some propulsion systems. It will generate lift similar to a wing, resulting in a net force forward, adding to the thrust generated by the propeller. In addition, the nozzle will limit the production of tip vortices which are a source of wasted energy. It also serves as an enclosure which will guard the propeller and prevent environmental damage or user injury. A number of effective duct geometries have been identified in industry and the Marin 19A shape was chosen for this system.

A rendered image of the ROV thruster along with a photograph of the assembled thruster is shown in figure 2.

Figure 2 – A Solidworks [6] rendering of the 400W thruster and a photograph of the assembled unit.

IV. SIMULINK MODEL

In order to predict the dynamic performance of the system and to validate existing models, a detailed MATLAB Simulink model was created. It incorporates all aspects of the thruster including the motor, magnetic gear and propeller.

The governing equations of this system are shown below, with the relevant variables described in Table 1.

Motor Current:

$$v_{in} - K_m \omega_m = R_A i + L_A \frac{di}{dt} \quad (1)$$

Motor Torque:

$$\tau_m = K_m (i - i_0) \quad (2)$$

Motor Acceleration:

$$\alpha_m = \eta_m \frac{\tau_m - \frac{T_p}{G} - \tau_F}{Im + I_p/G^2} \quad (3)$$

Propeller Advance Ratio:

$$J_s = \frac{Vs}{nD} \quad (4)$$

Propeller Resistance Torque:

$$Q_p = K_Q \rho n^2 D^5 \quad (5)$$

Generated Thrust:

$$T_p = K_T \rho \, n^2 D^4 \quad (6)$$

Variable	Units	Description
v_{in}	V	Input voltage
i	A	Motor current
R_A	Ω	Armature resistance
L_A	H	Armature inductance
K_m	N*m/A V/rad/s	Motor constant
ω_m	rad/s	Motor speed
τ_m	N*m	Motor torque
i_0	A	No-load current
α_m	rad/s/s	Motor accel.
η_m	~	Motor efficiency
τ_F	N*m	Frictional torque
G	~	Gear ratio
Im	kg*m^2	Motor inertia
I_p	kg*m^2	Propeller inertia
J_s	1/rev	Advance ratio

V_s	m/s	Free stream vel.
n	rev/s	Prop speed
D	m	Prop diameter
Q_p	~	Prop torque
K_Q	~	Torque coeff.
T_p	N	Thrust
K_T	N*m	Thrust coeff.
ρ	Kg/m^3	Water density

Table 1 – Relevant variables, their units and descriptions.

The 400W thruster was tested in an open-water flume tank. Therefore the Simulink model will simulate a situation where the free stream velocity is set and the input power to the thruster is adjusted and the thrust is recorded. Simulation results for a sample propeller are shown in Figure. This propeller is designed to operate at 0.6 m/s and generate 30N of thrust at 1000RPM with a propeller efficiency of 0.38. The results confirm that the propeller will generate 30N of thrust at 1000 RPM and that efficiency is maximized within this operating regime. Overall system efficiency is limited to 0.28 due to frictional losses and motor efficiency.

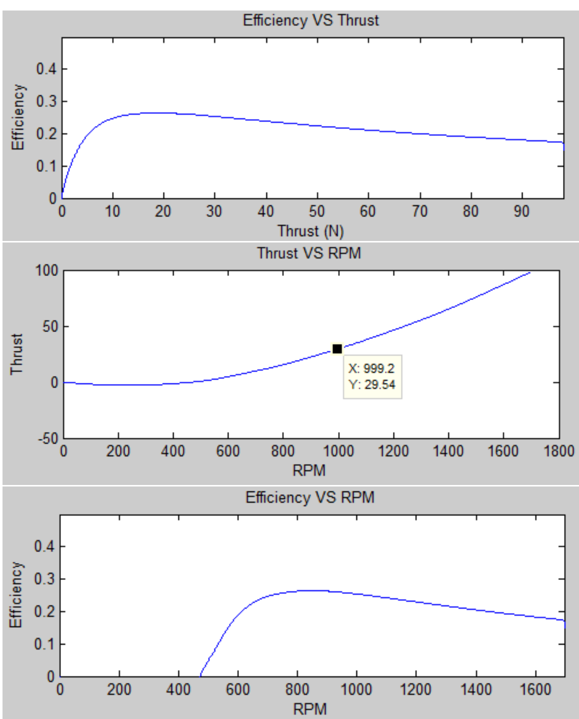

Figure 3 – These three graphs show simulated system performance data for a particular propeller geometry.

V. Performance Testing

The real performance of the 400W ROV thruster was determined throughout a series of trials in an open water flume tank. The tank is able to generate flow speeds between 0.3 and 0.7 m/s allowing a particular propeller to be tested at its designed operating point.

Flow velocity was measured using a Vectrino acoustic Doppler velocimeter. The thrust was measured by a beam-type load cell. The thruster is coupled to the load cell through a pivoting L-shaped bar. The experimental setup in the flume tank is shown in figure 4. The load cell was calibrated by applying known loads to the end of the beam and measuring the voltage output.

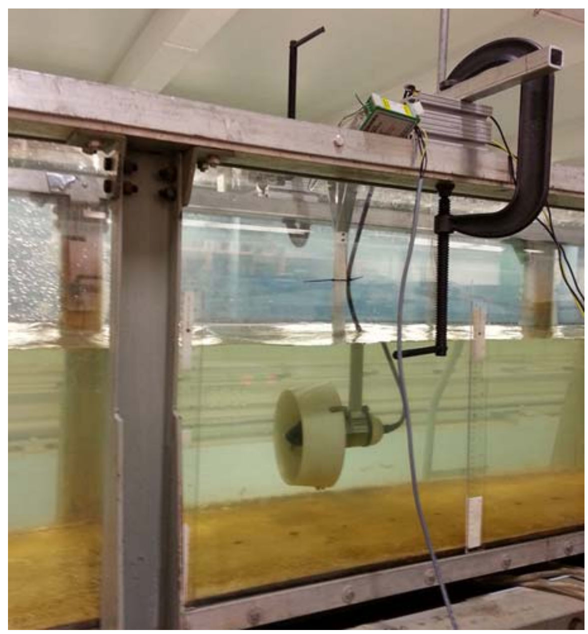

Figure 4 – Experimental setup of the 400W thruster within the open-water flume tank.

The first test performed was to confirm a performance advantage of using a duct. An arbitrary propeller optimized for use with a duct was designed using OpenProp and then tested with and without the duct installed. The thrust generated by the propeller as a function of motor voltage is shown in figure 5. The thrust as a function of motor current is shown in figure 6.

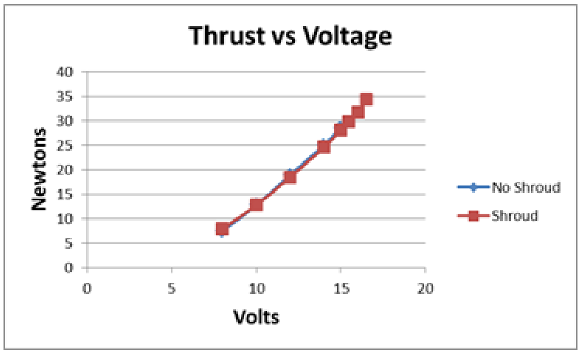

Figure 5 – Experimental data showing the thrust generated by the ducted and non-ducted propeller as the input voltage is increased. The thrust increase is considered negligible.

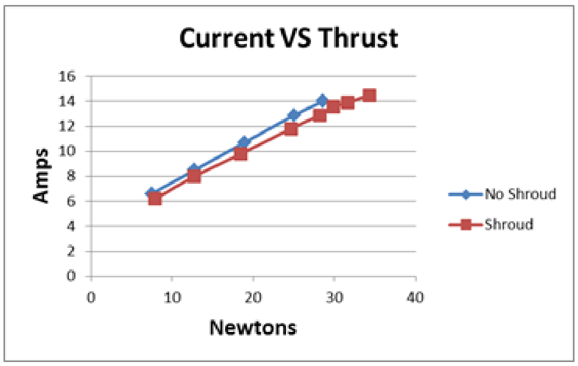

Figure 6 – Experimental data showing the electrical current drawn by the system for a given thrust, with and without the use of a duct. Current requirements are reduced when using the duct.

It is shown that the shroud generates a negligible amount of additional thrust. However, the current drawn and therefore the power required is reduced. This results in a net efficiency increase. The current drawn is proportional to the torque and the reduced torque means that more thrust can be achieved before the magnetic gear slips.

Although the results of this test were promising, it was noticed that the amount of thrust being generated by the propeller was significantly less than what was expected. A study on propeller design was performed to determine the cause of this discrepancy. Two unique propeller geometries were generated using OpenProp, each with a different operating point and geometric parameters. A summary of the designed propellers and their operating points is shown in table 2.

#	OD (m)	Blades	Thrust (N)	V_S (m/s)	RPM	η
1	0.127	6	65	0.5	2000	0.23
2	0.152	5	30	0.6	1000	0.38

Table 2 – The operating parameters and characteristics of three different propellers designed using OpenProp.

Two methods were available for manufacturing the propellers: FDM (fused deposition modeling of ABS polymer) and SLS (selective laser sintering of Nylon polymer). The two propellers were made in three versions. One version was FDM manufactured, SLS manufactured and SLS manufactured but with thinner blade profiles.

Each of the propellers was tested in the flume tank at its intended flow speed. Figure 7 shows how performance is affected by the different manufacturing methods. As expected, the thinner blades out-perform the thicker blades of the same material. The FDM propeller also performs better than both of the SLS propellers. This can be attributed to the smooth surface finish that FDM parts possess. SLS manufacturing produces raw parts with very rough and abrasive surface.

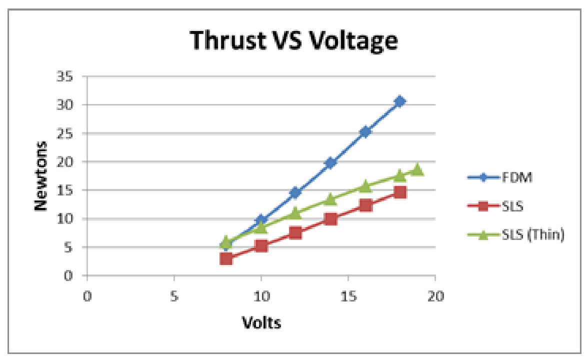

Figure 7 – The thrust generated by the three versions of propeller 1. Similar results were found for propeller 2.

VI. Performance Discrepancy

Figure 8 shows the flume tank performance of propeller 2 compared to the model results. When working with a computer model it's expected that actual results will differ, however significantly less thrust is being generated than expected.

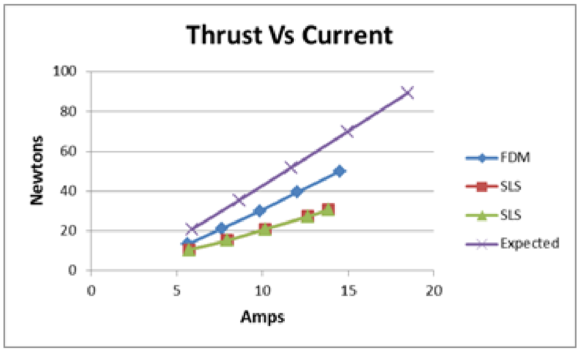

Figure 8 – Propulsion test results for propeller 2 along with its expected performance. Similar results were found for propeller 1.

This discrepancy could be the result of a number of factors. Results indicate that the propeller blade thickness and material selection play a significant role on performance. The ideal propeller would have a perfectly smooth surface finish with minimum blade thickness. Achieving a smooth surface finish is possible through polishing however, the blades must remain thick enough such that they maintain their shape and do not yield under the load.

It's believed that the flow quality in the flume tank is also a major contributor to the reduced performance. OpenProp considers constant, laminar free stream flow in an infinitely large body. However fluctuating velocimeter measurements indicate an unsteady and turbulent flow within the flume tank. In addition, the limited size of the tank would also result in irregular flow profile across the thruster. Bollard pull tests may produce results that better agree with the model. Bollard pull is a measurement of static thrust and requires no free stream flow, hopefully confirming the flume tank as a source of reduced performance.

The propeller hub design may also be a source for the lack of performance. OpenProp assumes a constant hub diameter however some of the propeller hubs were tapered. As a result, some portion of the propeller blade is actually "lost" as it resides within the hub. This missing blade area will result in a reduced thrust generation.

VII. USC THRUSTER DESIGN

The Autonomous Ocean Systems Lab is currently building a large spar-type unmanned surface craft known as the USC Sea Dragon. This vehicle will serve as test platform for a larger thruster.

CFD analysis was performed in order to determine the drag and therefore thrust requirements for each of three different operating modes of the Sea Dragon. These requirements are summarized in table 3. Two thrusters will be installed meaning each unit must only generate half of the required thrust.

Mode	Speed (m/s)	Required Thrust (N)
Cruise	1	140
Burst	2	550
Top	3	1200

Table 3 - Thrust requirements of the USC Sea Dragon

Because the vessel will be operating in the cruise mode most of the time, the thruster will be designed such that efficiency is maximized at this point. High efficiency is the result of a properly sized and designed motor-propeller system.

A parametric study was completed in order to determine the ideal propeller geometry using OpenProp. The first study was to determine ideal blade length. Based on the design of the vehicle the thruster's outer diameter is limited to 15 inches. Allowing room for the duct, the propeller is limited to 13 inches. Figure 9 shows the effect of propeller size on efficiency. It is clear that maximizing the propellers diameter will maximize the efficiency.

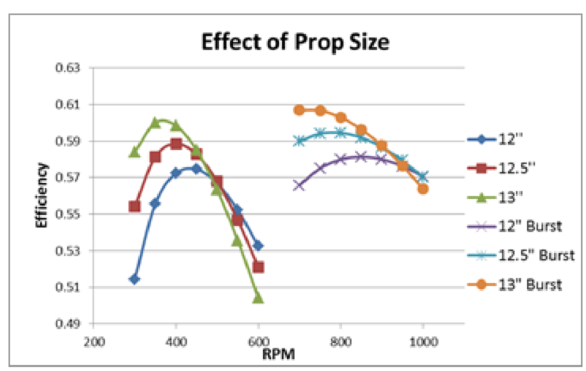

Figure 9 – Effect of propeller diameter on efficiency for cruise and burst operating modes.

A second parametric study was performed to determine the effect of blade length and the ideal number of blades. The results of the study for the cruising mode are shown in Figure 10. It is shown that for this particular case, the number of blades alone has little influence on the overall propeller efficiency, however different numbers of blades, perform best at different speeds. This was true for each of the operating modes. A propeller with three blades was chosen in an effort to simplify manufacturing.

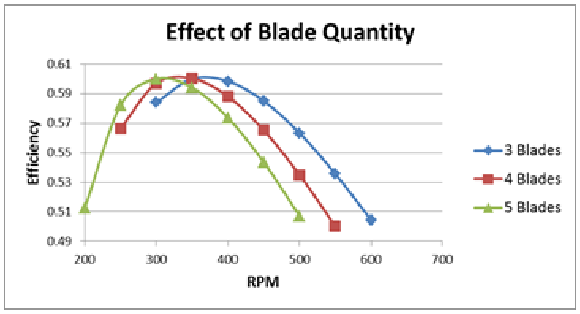

Figure 10 – The effect of blade quantity on propeller efficiency for a 13" propeller.

A final study was completed in order to determine the most efficient propeller speeds for each of the operating modes. This study was completed assuming a 13 inch propeller with 3 blades. The results of this study are shown in Figure 11.

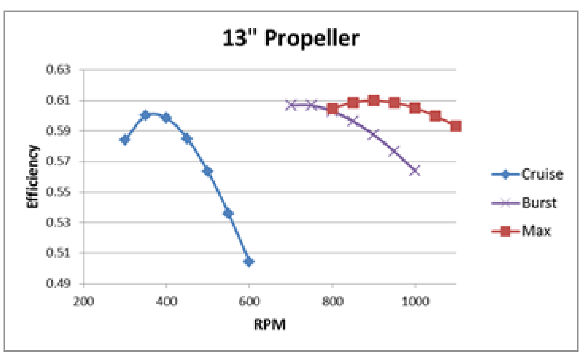

Figure 11 – Propeller efficiency versus rotational speed for each operating mode of a 3 bladed 13" propeller.

After determining the optimal propeller characteristics and operating points. OpenProp was used to generate the blade geometry as well as the propeller performance curves.

The magnetic gear used in the USC thruster is a radial type with a gear ratio of 1:8.5. An image of the gear topology is shown in figure 12. The sizing of the magnetic components was completed with COMSOL. By applying the propeller performance curves to the existing Simulink model, it was determined that 21 Nm of torque will be required to drive the propeller at its peak of operation. By varying the size of the magnets, pole pieces and air gaps, a suitable topology was determined. The COMSOL data providing the estimated torque capacity is shown in figure 13.

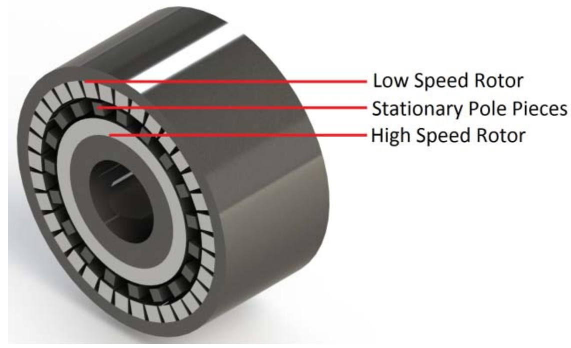

Figure 12 – A rendering of the magnetic gear topology used in the USC thruster. 4 magnets form the High Speed rotor and 34 magnets form the Low Speed rotor, resulting in a 1:8.5 gear reduction. 19 pole pieces provide flux harmony.

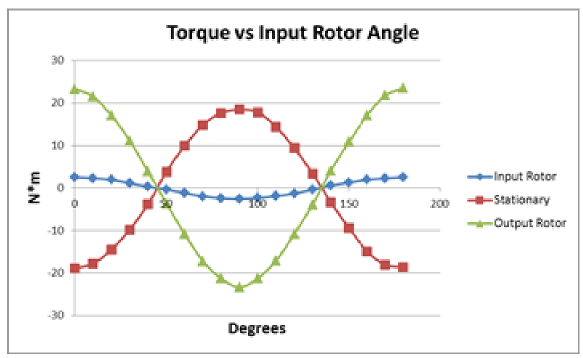

Figure 13 – COMSOL data showing the torque felt by each rotor. The output rotor can transmit 24 Nm before the gear will slip.

A brushless type DC motor was chosen due to its improved efficiency and better ability for monitoring speed and torque. Rather than using an off-shelf motor, a custom winding scheme was determined using a lumped impedance model. A 12-tooth 40mm commercially available stator was the starting point for the study. With the required range of torque and RPM known, various winding schemes were modeled. Efficiency of the motor was maximized by increasing the percentage of wire fill used in the winding scheme. Voltage and current requirements were limited by the available power supply. The motor power requirements and efficiencies are shown in table 4.

Mode	V_{in} (V)	I_{in} (A)	P_{in} (W)	Efficiency
Cruise	46	2.4	112	0.956
Burst	93	9.6	898	0.963
Top	144	22.17	3195	0.949

Table 4 – Custom motor power requirements and efficiency for the three operating modes.

According to the theoretical model it is expected that the thruster will be able to operate with an overall system efficiency between 0.5 and 0.6. This would be a significant improvement over existing ROV thruster systems. A rendering of the USC Thruster is shown next to a photograph of its current state of assembly in figure 14. Assembly is 95% complete with the only uninstalled items being the nose and strut fairings. The unit has been powered up on a bench to verify operation.

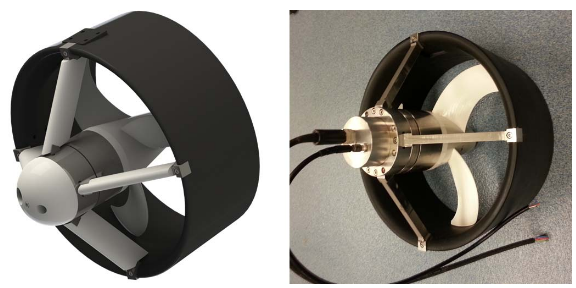

Figure 14 – Solidworks rendering of the 3000W thruster along with a picture of its current state of assembly.

VIII. CONCLUSIONS AND FUTURE WORK

This research has shown the overall potential of a magnetically-geared underwater propulsion unit. The quiet operation of the magnetic gear and its characteristic overload protection are valuable features in many applications. The expected efficiency boost is especially important for extended mission lengths or higher thrust requirements in smaller packages. The initial performance tests indicated that less thrust was being generated than expected however several sources for this discrepancy have been identified. Unstable flow in the flume tank as well as imperfections in propeller and blade design will have a negative effect on performance.

The future work will concentrate initially on improving the performance of the small 400W thruster. Before testing the large thruster it is important to validate the current computer model and ensure its accuracy. A new propeller with a constant hub diameter will be designed for the small unit and will be tested in a large static tank to determine the bollard pull. Subsequently, dynamic testing will be carried out in a larger flume tank or a tow-tank.

Once the large thruster has been initially tested and proven, two new 3000W thrusters will be manufactured. Some minor design changes have already been made that should result in a more compact system. These two new thrusters will be installed on the USC Sea Dragon for sea-trials

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