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System Identification of Underwater Thrusters with Driver Electronics

EE558 Project Report

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1 Table of Contents

2 Introduction

Underwater can be new popular area which people want to observe. We know a lot about the air we do not have enough information for underwater. However, moving underwater is a lot harder than the air, so the efficient control is an important issue. Since the thrusters are the most common way to move underwater and there is not enough research on the device, I decided to do system identification of underwater thrusters in this project. During the project, I have used the identification and estimation methods that I had learnt in the class.

3 System Identification of Underwater Thrusters with Measurements

For the system identification of the underwater thruster, it should be explained that the thruster system cannot be considered standalone without its driver circuitry. Since mostly brushless DC motors (BLDC) have been used in the underwater thruster systems, standard first principle models of brushed DC motors cannot be used for system modeling. BLDCs cannot commutate just by applying voltage or current, they require rotating magnetic field to commutate. To achieve that, sensitive position sensing of the peak of the magnetic field generated is required. Then, the driver circuity generates a "unipolar" or "bipolar" pulse width modulated signal to commutate the BLDC according to the angular position of the peak of the magnetic field.

The sensing systems also differ a lot; the magnetic field can be sensed by using back emf of the stator windings or separate hall effect sensors can be used. Both techniques have advantages and disadvantages according to the application, I will not go into the details for this report. However, I need to notify that the system's response changes a lot with the sensing method. In addition to that, there are 2 types of BLDC motors called "inrunners" and "outrunners" which differs according to the location of the rotor (inrunners, rotor is inside of the stator; outrunners rotor is outside of the stator). They have different applications for example inrunners can be a lot faster than the outrunners while outrunners can generate more torque.

In addition to that, to meet the application requirements BLDCs are generally controlled by a software. For example, in quadrocopters, one does not want fast responses from the motor to be able to control the system, or in case of underwater even you apply an input changing fast, water does not allow the thruster to respond fast. To overcome these issues, the commutation signal is generated according to the application, hence the software.

So, I have explained all these because I wanted to notify that, the thruster systems which are using BLDC motors cannot be thought without their driver circuitry because the response cannot be modeled without knowing all the parameters (Commutation signal type, rotor type, sensing method and software). Since all these parameters could change the response significantly, the thruster system and its driver circuitry can be though as gray box.

For the system identification of this system, I and Emre has developed a measurement system whose details will be given in the next part of the report. In short, we have applied a digital input signal to the system and measured the thrust, current and voltage applied. For the scope of this lecture, I will go into the details of thrust only. The sampling period of the system was 89ms and its accuracy is also measured by measuring the time between each consecutive measurement.

After some trials and calibrations, I applied consecutive step inputs with increasing magnitude to the system. To overcome the effect of previous measurement, the system was stopped for a while and then another input is given. With each pulse, the motor is rotated to opposite direction. To prevent permanent damage to the motor, I could not apply all the allowed speeds since when the highest input is applied, the current exceeds the maximum allowed according to the specification sheet of the motor.

The output of the system (thrust) is measured by a load cell system which is fastened at the edge of the test pool. The thrust generated by the system is applied to it with a lever system. The measurement is multiplied with some constant accordingly.

The input and the measurement signal can be seen in the figure below:

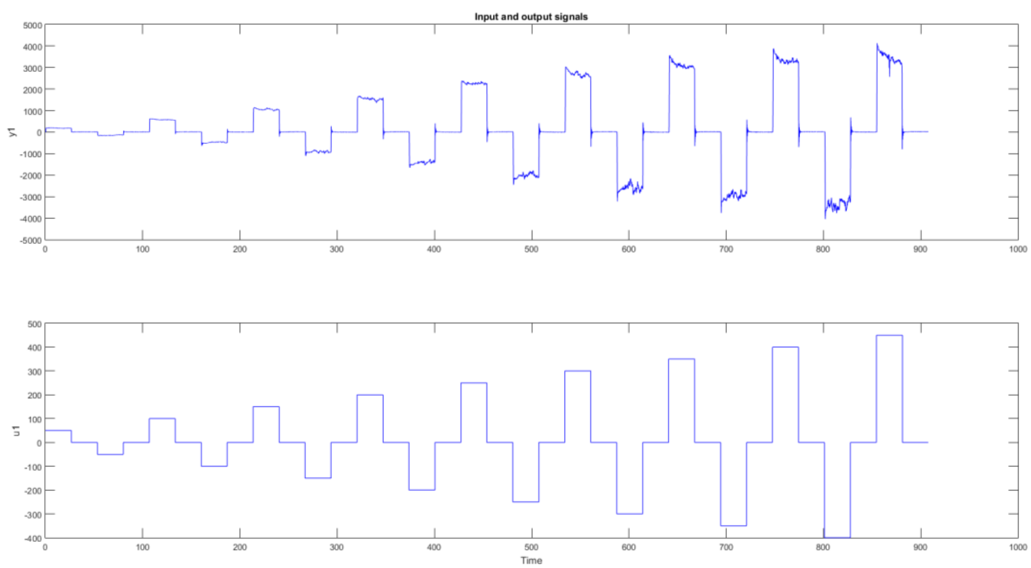

Figure 1: Output measurements of the system with applied input, unit of the output is grams, unit of the input is us

When the measurements are filtered by moving average and map to a single position, some rough sketch given below could be found:

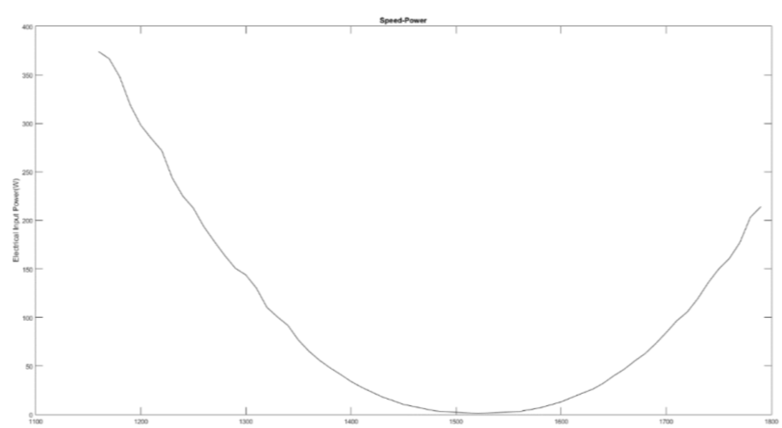

Figure 2: Speed-Thrust characteristics of the system, due to electrical limitations upmost speeds are not tested in forward direction. Left part of the graph is absolute value of the thrust

Just by looking at the figure above, one could say that the system is not linear.

To overcome the identification problem, Mert and I proposed to do a separate system identification for each step input. I separated the measurements and inputs into 17 pieces which corresponds to each step I have applied. The parts can be seen below, each color corresponds to another step input:

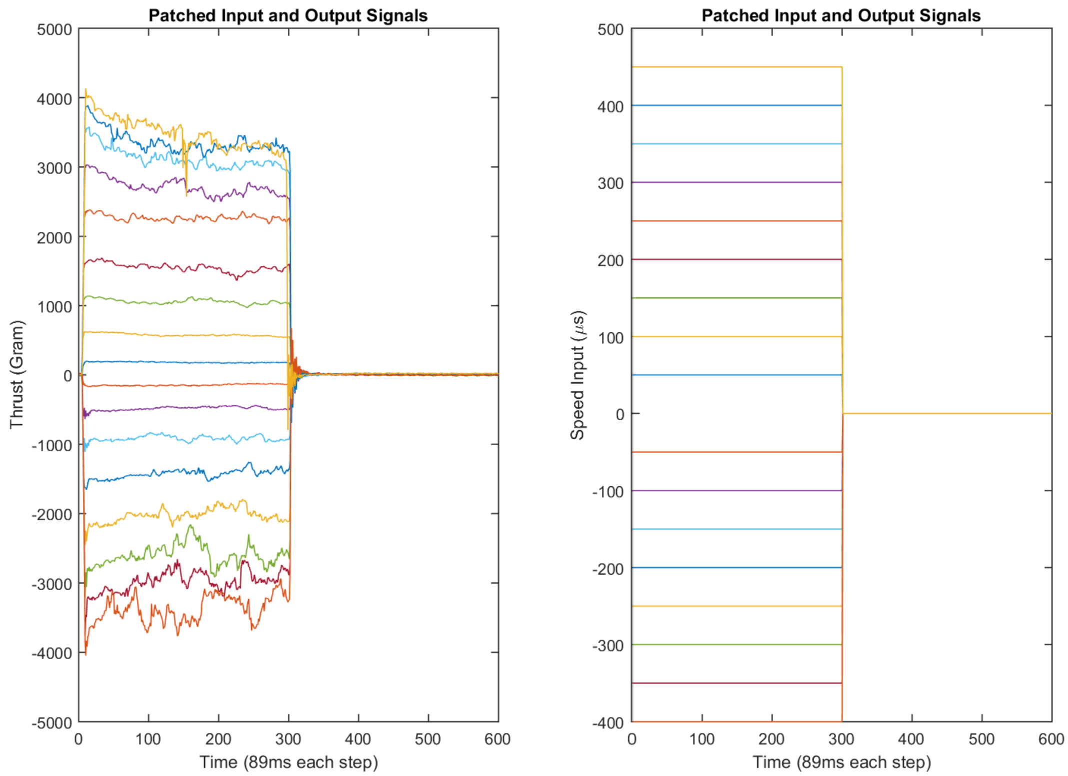

Figure 3: Separated step inputs and their responses

By looking at the figure above, one can understand that the response of the system changes with the given input.

For the identification, since the system is SISO, we have decided to identify the constants of the difference equation, hence the poles and zeros of the transfer function and to overcome non-linearity, we have decided to parametrize every constant of the transfer function to also be the function of the input.

Another issue is finding the number of poles and zeros of the system since we do not have specific model. One can assume that the BLDC motor inside of the thruster is 2nd order system but identifying the driver circuitry is not applicable. To find the optimal number of poles and zeros, the MATLAB conde we have written tries every combination of (pole, zero) number pair up to (10,10) with linear LS, maximum likelihood and MAP estimator. For last two I simply assumed that the error sigma is 1e-3 and I used the result of the linear LS as aposterior information for MAP estimator.

For every case (Different pole, zero numbers for each estimator), I identified the system for every 17 step inputs:

- Created the transfer function with these estimations
- Calculated the estimated output
- Calculated the residual error
- Sum them up to get the least residual error.

For every estimator, the optimal numbers were 5 poles and 1 zero case. So, I created the model as:

$$y[n+1] = a_2 y[n] + a_3 y[n-1] + a_4 y[n-2] + a_5 y[n-3] + a_6 y[n-4] + b_1 u[n]$$

Where

$$a_k = f_k(u[n]) \text{ } where \text{ } k = 2,3,4,5,6$$

$$b_1 = g(u[n])$$

With this knowledge, I identified a_k values and b_1 for every 17 step inputs and found the constants by using linear LS estimator. I also applied MAP and MLH too, but results differed with only 1e-8 for each value.

By using these a_k values and fitting these values to a polynomial, I have found every f_k functions. There are also 2 different versions of them for both forward and backward directions since the geometry of the system is different for each direction.

4 Results

After the identifications with 5 poles and 1 zero, the numerator and denominator constants for every 17 inputs are given below:

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	50	-50	100	-100	150	-150	200	-200	250	-250	300	-300	350	-350	400	-400	450

Figure 4: Applied step input sizes for each, negative inputs corresponds to backward rotation

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1	1.1602	1.0810	2.5514	2.4449	3.2861	3.1860	3.3241	3.2483	3.8464	3.2125	3.2280	3.2055	3.1284	3.0473	2.8980	2.7945	1.1046

Figure 5: Numerator constants for every 17 step inputs

	1	2	3	4	5	6
1	1	-0.8152	0.0813	0.0772	-0.0750	0.0486
2	1	-0.6354	-0.0889	0.1018	-0.0903	0.0842
3	1	-0.7123	0.1339	0.0081	-0.0119	0.0223
4	1	-0.5470	0.0093	-0.0794	0.1427	-0.0204
5	1	-0.7054	0.2214	-0.1709	0.1902	-0.0708
6	1	-0.5667	0.0528	-0.0968	0.1816	-0.0503
7	1	-0.7380	0.2130	-0.1839	0.2443	-0.1073
8	1	-0.7001	0.1487	-0.1531	0.2213	-0.0621
9	1	-0.6790	0.1004	-0.1390	0.2697	-0.1284
10	1	-0.7061	0.0547	-0.1116	0.2704	-0.1114
11	1	-0.7665	0.0724	-0.0953	0.2547	-0.1082
12	1	-0.7318	0.0319	-0.0652	0.2405	-0.1062
13	1	-0.7825	0.0920	-0.1451	0.3116	-0.1246
14	1	-0.7432	0.0323	-0.0778	0.2777	-0.1310
15	1	-0.7678	0.0759	-0.1435	0.2828	-0.1018
16	1	-0.7946	0.0972	-0.1504	0.2845	-0.1055
17	1	-1.0833	0.0568	-0.0158	0.3406	-0.1526

Figure 6: Estimated denominator constants of the transfer function for every step input

I applied 3rd order curve fitting to these values (It gave the best results) to get the functions given below:

	1	2	3	4
1	-1.4179e-08	5.2409e-06	-1.7431e-05	-0.7951
2	2.0271e-08	-1.6948e-05	0.0039	-0.0749
3	-9.2440e-09	1.1619e-05	-0.0040	0.2585
4	1.4026e-08	-1.4225e-05	0.0050	-0.3180
5	-8.3603e-09	8.1435e-06	-0.0027	0.1817

	1	2	3	4
1	-2.1019e-08	-1.5077e-05	-0.0025	-0.7024
2	-3.2656e-08	-2.4832e-05	-0.0058	-0.3320
3	4.2803e-08	3.2016e-05	0.0073	0.3897
4	-2.8051e-08	-2.3565e-05	-0.0065	-0.3449
5	4.7551e-09	5.6782e-06	0.0022	0.1716

Figure 7: Fitted curve coefficients for the denominator constants for forward direction at the top, backward direction at the bottom

	1	2	3	4
1	-1.8088e-07	-1.6699e-04	-0.0471	-0.8306

	1	2	3	4
1	-1.9494e-09	-5.8309e-05	0.0297	-0.0320

Figure 8: Fitted curve coefficients for the numerator constants for forward direction at the top, backward direction at the bottom

4.1 Denominator Functions

4.1.1 $f_2(x)$

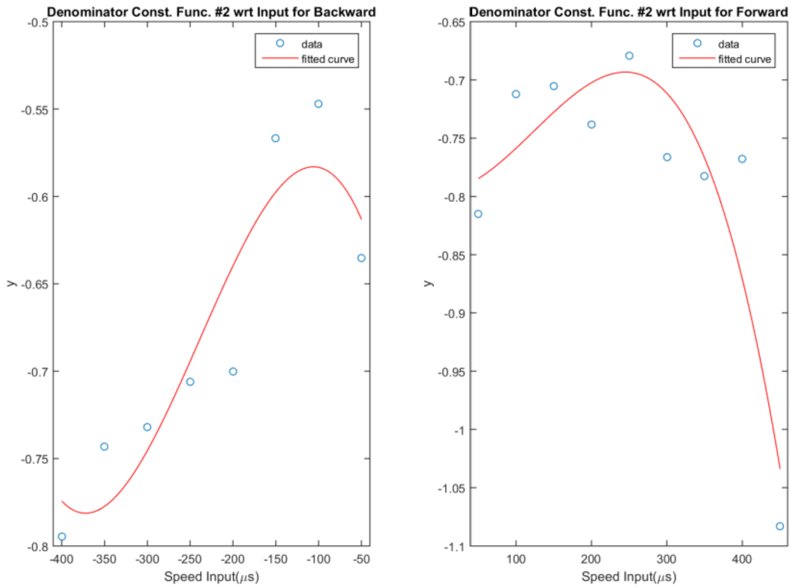

Figure 9:f_2 function

4.1.2 $f_3(x)$

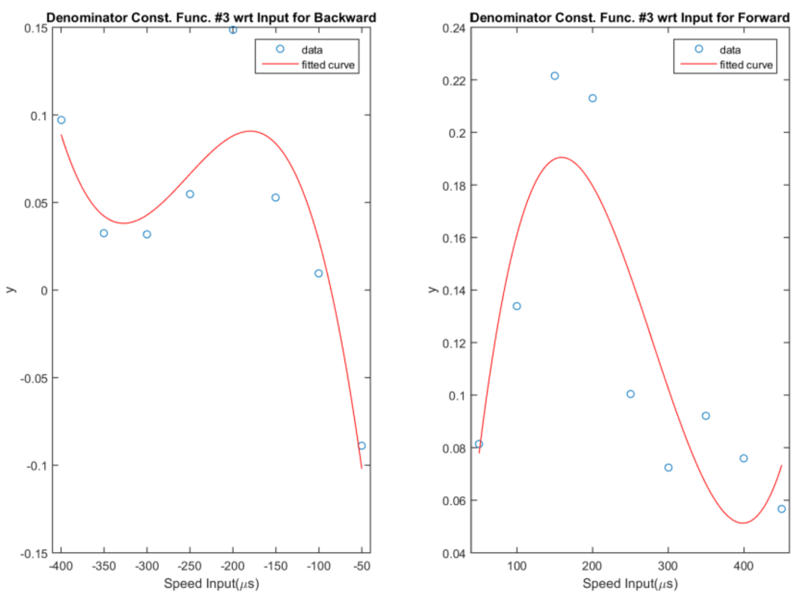

Figure 10:f_3 function

4.1.3 $f_4(x)$

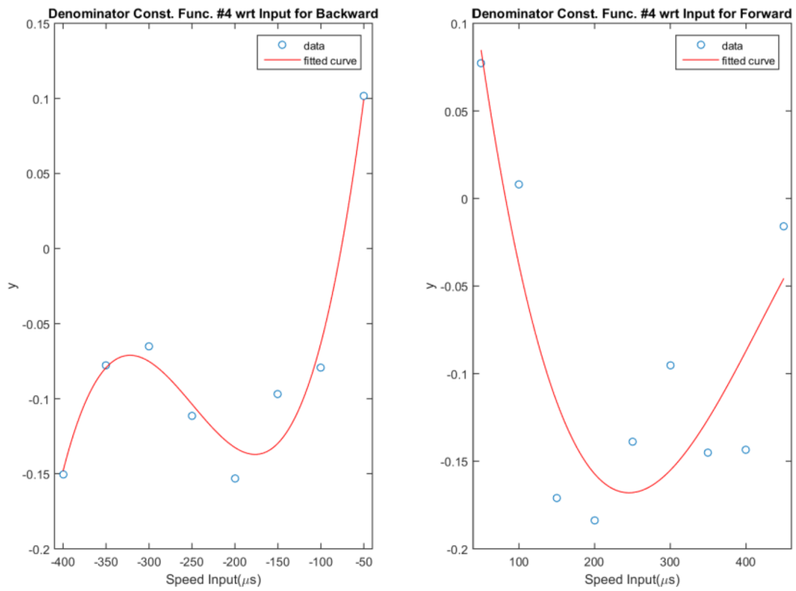

Figure 11:f_4 function

4.1.4 $f_5(x)$

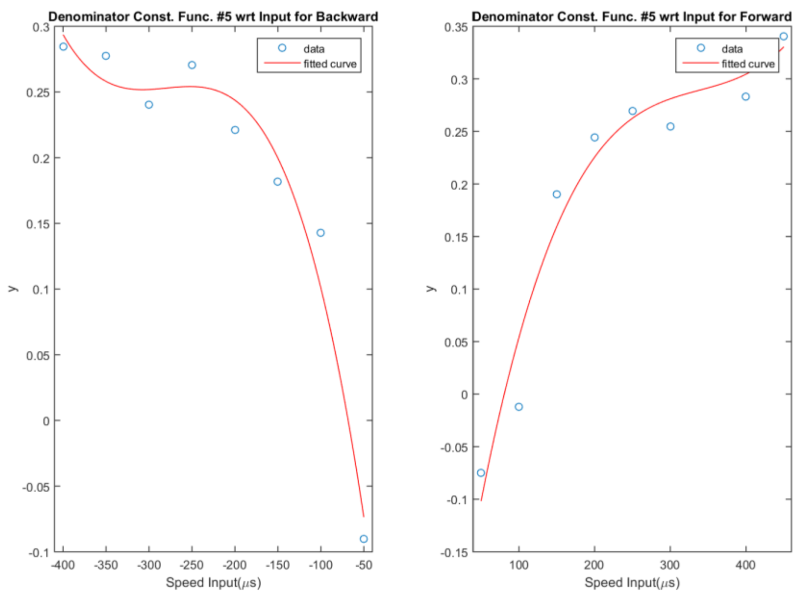

Figure 12:f_5 function

4.1.5 $f_6(x)$

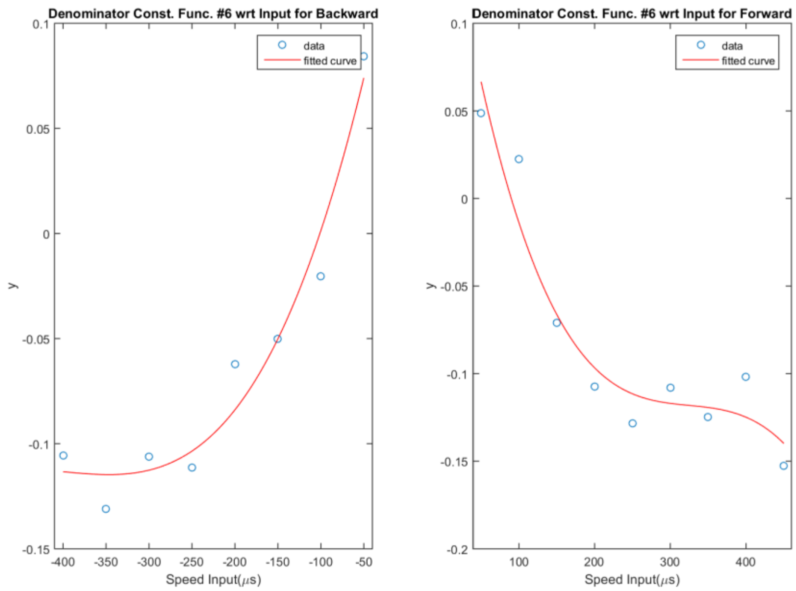

Figure 13:f_6 function

4.2 Numerator Function

4.2.1 g(x)

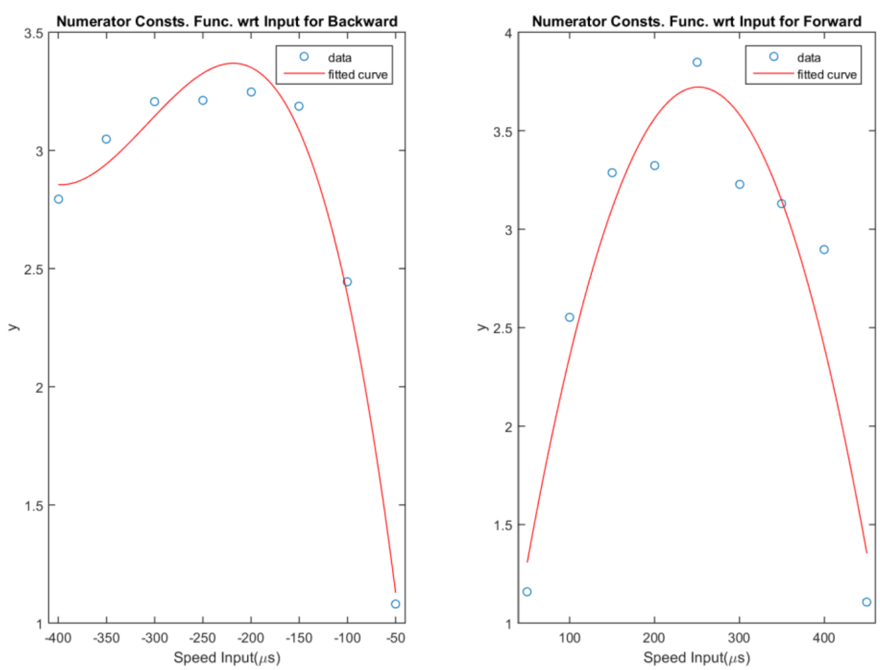

Figure 14: Numerator Constant Function

5 Conclusion

In this work, using the estimators and the identification methods during the EE558-System Identification and Adaptive Control class, I have identified a parametrized transfer function of the underwater thruster commutated by a BLDC motor and its driver circuitry. Since there are a lot of parameters of the underwater thruster, its mathematical model cannot be formed easily. Other than finding a model directly, in this project I have approached the system as grey box. I have applied different step inputs to the system and measured the thrust generated by that using a load cell then identified the system for each step inputs using linear LS, MLH and MAP estimators. Each step input corresponds to a locally linear region. Using all the estimated parameters for each step input, then I estimated the polynomial functions which describes the nonlinear behavior of the system. For the future work, I will implement a controller using this model and try to control the thrust generated by the system.