OSCILLATING FIN THRUSTERS FOR MULTI-VIEW CLASSIFICATION MANEUVERING ON MCM UUVS

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***Abstract* - Nekton Research and Florida Atlantic University have integrated a hovering module onto the Morpheus UUV. This module uses flexible oscillating fin thruster (OFT) technology. It provides Morpheus with the ability to stop, hold station and operate in heave and sway. These capabilities, previously unavailable, will allow Morpheus to execute delicate tasks such as mine classification. Herein, we discuss the development of the OFTs for Morpheus, results from sea trials and ideas for how to add OFTs to existing vehicles engaged in MCM operations but without the ability to hover.**

I. INTRODUCTION

Shallow-water mine-hunting (MCM) vehicles must operate under challenging conditions. The ability to swiftly fly close to the seafloor, stop, hover, and accelerate is crucial to mission success. As bottom mines become more cryptic, current techniques of "fly-by" single pass target identification become less reliable. More robust, multi view classification techniques will require future UUVs to hover and slowly rotate around targets, a technique that cannot be performed by today's MCM UUVs. Oscillating Fin Thrusters (OFT) are multi-purpose actuators capable of delivering large and sudden amounts of thrust in a controlled fashion as well as functioning as fast response-time control surfaces and multi axis maneuvering thrusters [1-3]. Fitting existing vehicles with flexible OFTs can help deliver the performance required for MCM as well as other maneuvering sensitive missions like ship hull inspection.

The main objective of this work was to develop an OFT module and to retrofit FAU's Morpheus UUV with it. Building on previous ONR-sponsored research of OFT thrust generation, the mobility module operates in three distinct modes: (1) hovering and low speed maneuvering; (2) obstacle avoidance, i.e. controlled delivery of large, three dimensional, thrust impulses; (3) control surface mode, i.e. providing controlled delivery of lift [1-4]. Achieving these goals involve three phases: (1) module construction, (2) controller development, and (3) optimization of the OFT components. Refer to [5] for a more detailed description of the OFT module and the preliminary testing.

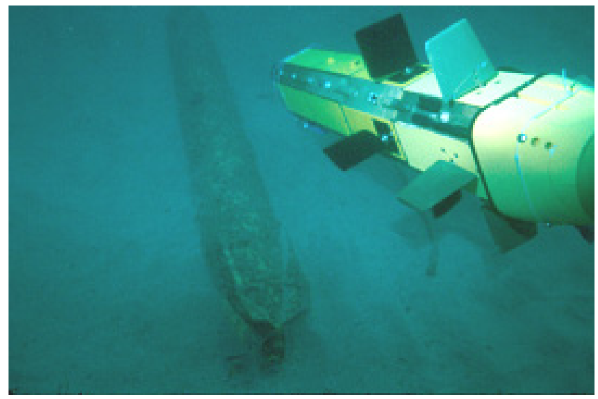

Figure 1: Morpheus using four OFTs (black fins) to generate the yaw, sway and heave motions required to perform a multi-view classification maneuver around the torpedo in the foreground.

II. OFT Development

A study was performed to measure the effect of fin geometry and composition on efficiency. Fourteen different fins were built to test the effect of fin flexibility and aspect ratio. A waterproof Nektor actuator was mounted to a six-axis load cell (JR3, 100M40A, 0.1N resolution) and data was collected at 100 Hz using a Matlab interface. The Nektor and load cell were mounted to the bottom of the 0.8m x 0.8m x 1m working section of Nekton's flow tank that is capable of speeds up to 1 m/s (Figure 2).

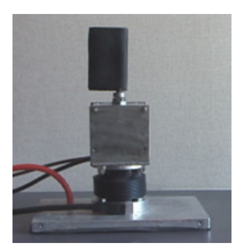

Figure 2: Nekton's flow tank and OFT loadcell

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A. Fin test results

We found that flexibility did not affect the efficiency (Table 1). At a given frequency and amplitude, a more rigid fin produced more thrust but required more torque. Thus, fin flexibility selection can be made on the basis of durability and resistance to impact rather than performance. We found however that the aspect ratio had a drastic impact on the efficiency. The efficiency was optimal for an aspect ratio of 1, being 60% higher at that point than above and below it. Thus, a square fin was selected (Table 2 and Figure 3).

Table 1: Effect of flexibility. Chord = 4", span = 6"

Flexibility (shore)	Bollard Efficiency (%)
25	30
40	28
60	30

Table 2: Effect of aspect ratio. Flexibility = 40

Span/Chord	span,chord (in,in)	Bollard Efficiency (%)
0.67	4,6	35
0.83	5,6	40
1	6,6	50
1.2	6,5	35
1.5	6,4	28
1.75	7,4	30
2	6,3	22
2	8,4	32

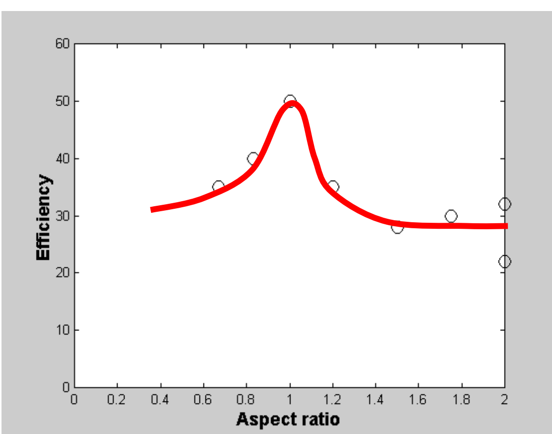

Figure 3: Effect of aspect ratio on Bollard efficiency

II. OFT Integration

It will take many years of scrutiny and careful consideration before the relatively conservative UUV community embraces OFTs on operational vehicles. Fortunately, FAU's Morpheus UUV was designed for easy integration of accessory payloads. We were able to build a stand-alone module to allow us to begin learning how to use OFTs to provide the thrust necessary to perform real Navy missions on a fielded UUV. This module could be temporarily added to Morpheus and as such did not require the base vehicle to be altered.

A. Multi view Classification Maneuver Controller

In addition to the module hardware and fin control software described previously [5], vehicle controllers were needed for the new maneuvering capabilities. Linear proportional controllers were developed for heading, sway, emergency stop and a multi-view classification maneuver. In addition, we experimented with three adaptive controllers for single point hovering, sway and a square box pattern with a constant heading. In this paper, we present a discussion of the multi-view and emergency stop controllers only.

This maneuver allows the UUV to slowly rotate around a target while training nose mounted sensors, e.g. a camera, or sonar, on the target in an effort to get a view of all exposed sides. To perform this maneuver, the vehicle must blend movements in the sway, yaw, and surge axes while maintaining a constant altitude (heave axis). While a single, four-fin module is capable of generating thrust to maneuver with six degrees of freedom, the mid-body location used on the Morpheus integration had low performance in most motions. This is due to the short moment arm between the OFTs and the center of rotation. The module was positioned approximately 2/3rds of the way between the bow and stern. It has been seen that the position of the OFT module behind the center of mass of the vehicle has an influence on its motion that favors the multi-view maneuver. Here, the moment created by the lateral force helps to achieve the desired rotational motion needed to turn around a target. The heading controller needs to control this moment to follow the

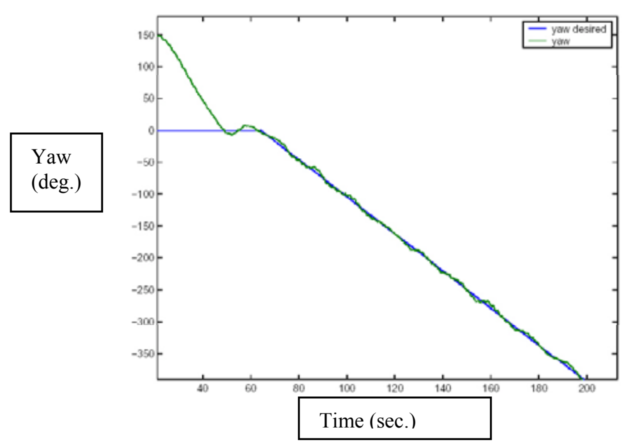

Figure 4: Heading and desired heading during the classification maneuver. The vehicle is slowly rotating.

desired heading, and not to fight against it. Figure 4 shows how well the vehicle tracks the desired heading. For the first 60 seconds the UUV is heading to 0 degrees, and then it starts to turn around the target. It takes about two minutes to go around the entire circle. The heading error shown in Figure 4 is very good: it stays between -10 and +10 degrees during the entire maneuver.

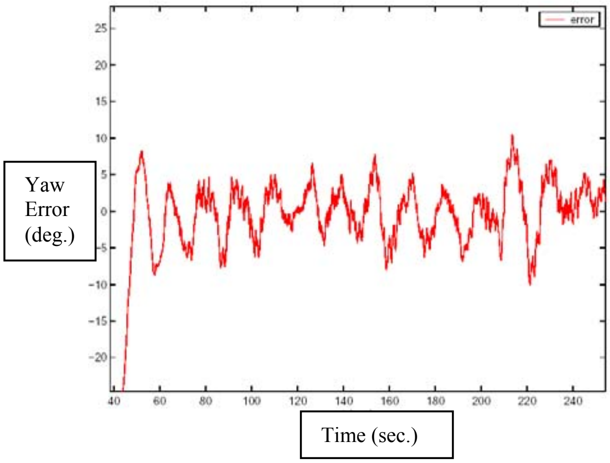

Figure 5: Error on the heading during the observation pattern

B. Emergency-Stop Controller

As MCM UUVs travel between and near seafloor targets there is a constant risk of impact with obstructions. While forward looking and obstacle avoidance sonars can mitigate this risk, it would be advantageous if the UUV were able to stop quickly. One of the attributes of OFTs is their ability to generate large forces quickly [6].

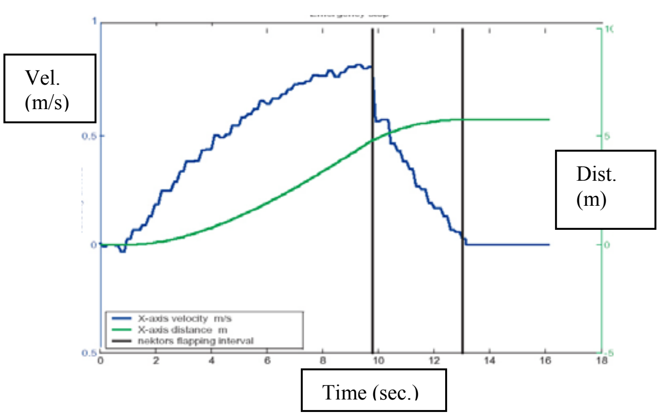

Figure 6: Velocity and distance during Emergency Stop maneuver

The goal of this controller is to simulate the detection of an obstacle in front of the UUV, requiring an emergency stop. The results from this experiment are shown in Figure 6. The UUV was programmed to stop after 4 meters. The blue plot represents the velocity of the vehicle along the X-axis. The green one represents the distance traveled. The vehicle acceleration can be seen for the first 4 meters, then deceleration after that. The two black vertical lines indicate the time interval where the OFTs are oscillating. It starts just after 9 meters, and stops when the velocity is equal to zero. The UUV reaches a velocity of 0.8 m/sec in 10 sec, and stops in 3.5 sec. During this 3.5 sec interval, the vehicle travels an extra 0.9 meters. This means that a Morpheus equipped with an OFT module and a sensor able to detect an obstacle 1 meter in front of it should be able to stop just before the collision. This can be useful when the obstacle is potentially dangerous for the UUV, like a mine.

III. Conclusions

A retrofit module was designed and built for Morpheus that demonstrates how OFTs can be used as maneuvering thrusters and emergency stop devices while not significantly affecting the cruising performance or existing launch and recovery procedures. The module proved to be very reliable and mechanically robust. Control of the OFT module proved challenging as this is a completely new system and unorthodox control techniques, like antagonistic force balance, were adopted to address some of these challenges. We are still in the infancy of our ability to use OFTs in a precise and efficient manner, but it is apparent that OFTs will be valuable tools in the future. Our next steps are to develop OFT modules for the REMUS and Ranger UUVs. In parallel, we are advocating that designers of future vehicles consider dual function OFTs that work as control surfaces while cruising and maneuvering thrusters for hovering and obstacle avoidance.

IV. Acknowledgements

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V. References

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