Results from Mechanical Docking Tests of a Morpheus Class AUV With a Dock Designed for an OEX Class AUV

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Abstract- This paper reports on a series of experiments done to test the feasibility of docking a Morpheus class autonomous underwater vehicle (AUV) on a dock originally designed for the much larger OEX class AUV. These tests were designed to observe the reaction of the vehicle upon impact with the dock and determine the success rate of the mechanical system. The tests were done at sea with the dock resting on the sea floor using divers to start and stop the vehicle for each run. Diver observations and video, as well as logged vehicle sensor data were then used to draw conclusions on the viability of the docking system.

I. Introduction

The ability to dock an AUV is a key component in longer term missions. Docking allows an AUV to recharge batteries, download collected date, and upload new mission plans. The use of a dock in an AUV mission could create and enormous saving in manpower and ship time for the collection of spatial and temporal data- limited only to deployment and recovery of the vehicle and dock. In other situations, operating an AUV without a dock could be difficult or impossible. An example of such a situation is making oceanographic measurements just before, during and just after a storm front passes an area.

The docking system being developed at FAU has the following characteristics: it's relatively small and portable, fairly inexpensive and has a passive capture mechanism. Additionally, using the nose of the vehicle for a capture point was avoided.

Work has been done for the last several years at Florida Atlantic University on an AUV docking system. This system was originally developed for the OEX class vehicles [1,2,3,6,7,8]. The work presented in this paper was in an effort to implement the docking system for use with the Morpheus class vehicles [5].

II. Morpheus AUV

The Morpheus is a relatively small, modular autonomous underwater vehicle. Four separate pressure vessels (modules), a nose section and a tail section make up the base vehicle. Each of the modules are about 12 inches long and 9 inches in width and height. Because of this modularity, as well as the software architecture, the base modules can be easily interchanged between vehicles. This modularity also allows additional modules containing payloads to be added easily.

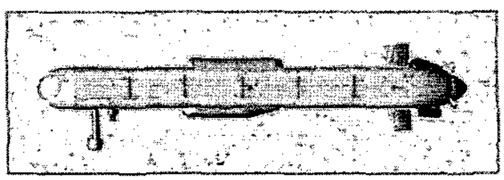

Figure 1. Morpheus with docking payload

The docking payload is a flooded module that holds the "docking stinger". The stinger is a fiber reinforced plastic shaft that hangs below the vehicle with a "docking puck" attached to the end. The connection

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between the vehicle and the stinger is a damping system that helps lessen the shock when the vehicle impacts the dock. The damping system is a rubber cylinder that is held inside a rigid cylindrical mount attached to the vehicle. The stinger shaft then runs through the center of the rubber cylinder.

The prototype docking payload used a full module 12 inch module, but this length will be reduced in a future version.

III. Dock

The dock being developed was originally designed for use with the OEX class AUV. The OEX has a mass of approximately 800 lbs. compared to approximately 200 lbs. for the Morpheus. The damping system was originally designed to be in the form of the entire dock rotating about it's base to absorb the vehicle impact. Because of the reduction in mass however, the afore mentioned, much simpler damping system was used on the Morpheus.

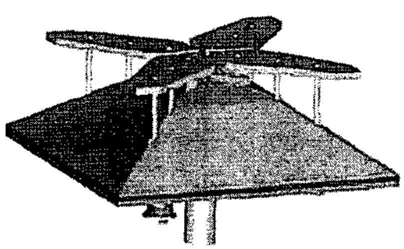

Figure 2. Morpheus dock

The basic dock design consists of a pyramid base with a guide above the intersection of each of the sides. The capture point of the dock is located at the top of the pyramid. This configuration is designed so that the vehicle has the option to dock from four different directions. This is so that the approach direction can be at least somewhat into any existing current and thus reduce the impact speed without altering the water speed (under a certain water speed the vehicle will become less responsive to control inputs).

If the vehicle approaches the dock below the capture point, the sides of the pyramid are designed to guide the puck at the end of the stinger up. If the vehicle approach is off to either side, the guides are designed to horizontally funnel the stinger shaft to the capture point. The resulting "window" that is created by this configuration which the vehicle must navigate to is about 12.5 inches vertically and 25 inches horizontally.

Once captured, the dock will charge the vehicle's batteries and download and upload data. The vehicle can then remain at the dock until it's next mission, at which time the horizontal guides move away from the center of the dock and allow the vehicle to float up from the dock.

IV. Docking Tests

The purpose of this set of docking tests was to determine the viability of the mechanical system. The series of tests included two days of testing with a "dummy" vehicle followed by two days of testing with the real Morpheus.

The initial tests were done with the dummy vehicle because the Morpheus was unavailable for docking experiments at the time. These tests were conducted in order to get a better sense of potential problems with the docking system. Additionally, the testing procedure could be refined to some degree. This would help minimize the time necessary to conduct tests with the Morpheus when it became available.

The dummy vehicle was constructed from empty Morpheus modules with weight placed inside each at a calculated position. This was done in order to get the weight and the center of gravity of the dummy vehicle as close as possible to that of the real vehicle.

Because the dummy vehicle did not have thrust or control, a spring loaded launching system was built that would propel the dummy vehicle off a guide pole and into the dock. The launcher and dock were mounted on the sea floor and the testing was conducted with divers.

The results of the tests with the dummy vehicle showed a fairly low success rate. A low percentage of the run ended with the stinger parting (or coming close to parting) the gates at the capture point and in many of those runs that were considered successful, the initial impact point was not far from the capture point. The primary mode of failure was due to the dummy vehicle loosing momentum before reaching the capture point. In some cases this occurred because the stinger, instead of impacting and then riding the ramp or guide to the capture point, would bounce back and forth several times between guides, before reaching the capture point. In other cases, because of the vehicle's low roll moment and small center of buoyancy - center of gravity separation, the impact with the dock could cause a large roll and cause the stinger shaft to jam in the entrance to the capture point and fully stop the vehicle.

From these tests it was concluded that for the docking system to have a chance of working the vehicle must provide thrust until it reaches the capture point. It was also concluded that the gates at the entrance to the capture point must be redesigned. Their design allowed any imperfection or marine growth to cause them to be very difficult to open.

Once the Morpheus became available, it was used for two more days of testing. The dock was again set up on the sea floor, but this time the vehicle approached the dock under it's own power. The vehicle was started from a point that was located 10 meters from the dock. This distance was calculated to be enough to allow the vehicle to accelerate to about two knots before hitting the dock. For these tests, two divers were used to start the vehicle, follow it to the dock, and take it back to the start point for the next run. An additional two divers were armed with underwater video cameras to record the vehicle's reaction when it impacted the dock.

For these tests the dock's gates were removed. The original gates had been fouled from marine growth when the dock was awaiting recovery from the sea floor. Even after cleaning the gates, because of the design, they were nearly inoperable. It was assumed that a gate could be designed that would offer little resistance to the stinger as it entered the capture point and therefore not having the gates on the dock for theses tests would still produce valid results.

On the first day of testing with the Morpheus, the vehicle was commanded to run at a set altitude with a fixed water speed and heading. From the start point the vehicle was aimed at the dock before starting the thruster. The set altitude turned out to be too high for the first dive and then over corrected too low for the second dive. This resulted in the vehicle having to be slightly guided into the dock by the divers.

In all, 30 runs were completed and the stinger hit within the docking window 15 times. Of the 15 times the vehicle hit within the docking window, the stinger went into the channel to the capture point, for what would be considered a successful dock, 13 times (87%). The initial impact locations had a fairly good distribution on the right side of the dock. Since the dock is symmetrical, the side which the vehicle impacted should not make much difference.

The same initial vehicle reaction that was observed in the testing done with the dummy vehicle and caused the vehicle to loose momentum also occurred with the real vehicle. With the real vehicle however, the constant force provided by the thruster was able to re-accelerate the vehicle, once it righted itself from any impact induced roll, and the vehicle would move to the capture point.

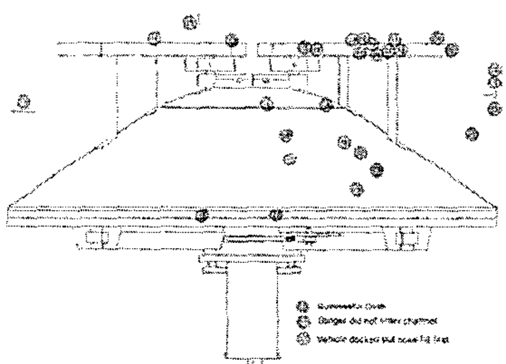

Figure 3. Initial impact locations for day 3 test

Because the divers were required to help guide the vehicle to the altitude of the dock, it was decided to run another day of tests and get the altitude setting correct. This was done by having several missions available for the divers to select with different altitude settings. The dock was also raised about 1.5 meters higher off the bottom because in the first day of testing with the Morpheus the doppler velocity log (DVL) was not far enough from the bottom for vehicle to record speed and position data.

On the second day of testing with the Morpheus, the altitude was adjusted to the correct setting and the divers did not interfere with the vehicle's flight to the dock. The stinger hit within the docking window 21 times of 39 runs overall. All of the runs where the stinger hit within the docking window either went in the channel to the capture point or appeared as if they would of without extenuating circumstances (a few cases where either the stinger constrains or stinger shaft broke or where the thruster shut off prematurely).

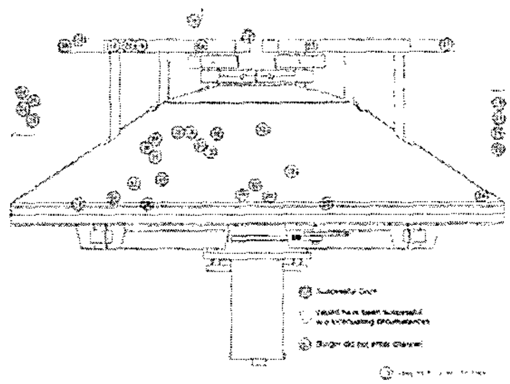

Figure 4. Initial impact locations for day 4 test.

V. Gate Redesign

The original gates installed on the dock had a flaw in the design which allowed the friction force countering the opening force to have the potential of becoming very large. The gates were designed to slide open in a direction perpendicular to the motion of the stinger motion. This caused the normal force to be relatively large and if the coefficient of friction of the sliding mechanism did not remain small, the friction force would be large.

In the tests done with the dummy vehicle, the original gates were installed on the dock. Before the dock was placed in the ocean, the gates operated reasonably well, but after being exposed to the marine environment for several weeks, the gates were fouled with marine growth. Once the dock was recovered from the ocean, the gates were taken apart and cleaned. However, due to small amounts of residue and the wear that had occurred on the gates, they were almost inoperable.

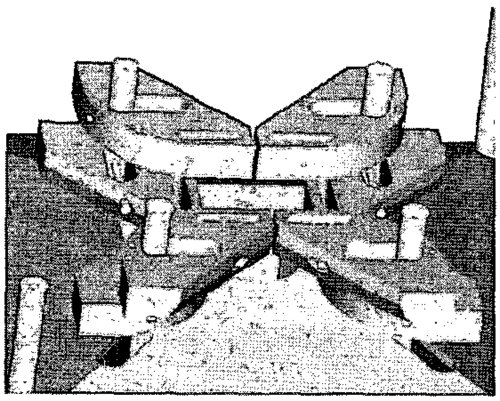

Figure 5. Old gate design.

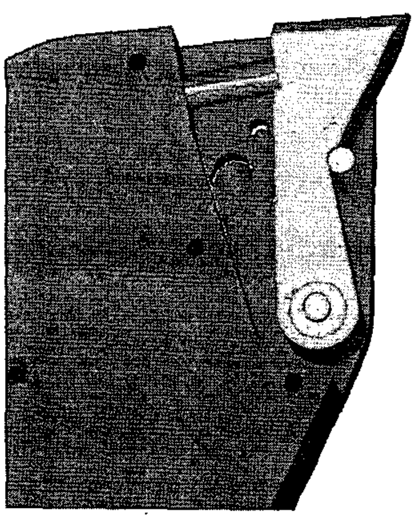

Figure 6. New gate design.

The force required to open the gates was determined from the worst case where the stinger shaft jams in the channel at the entrance to the capture point. In this case the thruster would have only the distance from the entrance to the gate to build the momentum required to open the gate.

The new gate design uses a wedge shaped gate that rotates to move out of the way as the stinger shaft moves past. The guides were made thicker and a pocket was machined out near the channel for the gates. A compression spring was fixed behind the gate to cause the gate to spring back behind the stinger after it passed and lock it into the capture point.

The new gates were built and installed on the dock. Tests of the new gates with the vehicle in the water have not yet been completed. From testing in the lab by pushing the stinger in by hand however, the gates appear to work very well.

VI. Results and Conclusions

The results from the tests showed that the dock has a good chance of being a viable design for use with the Morpheus. With the vehicle under power and when the stinger hits the dock within the docking window, the rate of what were considered successful docks was 94% (34 of 36). When implemented with a docking controller on the vehicle that is capable of bringing the vehicle around for another attempt at docking if it misses the dock, this system should be adequately reliable.

There is a small chance of damage to the vehicle's control surfaces (mainly the stern planes) or the propeller if the vehicle slightly misses the dock. There is only a very small area that the vehicle would have to fly through that would allow the propeller to come into contact with dock. The rudders are fairly protected because one is on top of the vehicle and the other is behind the stinger. The stern planes probably have the highest risk of damage, however, in order for there to be enough energy to damage them it would probably take a case where the fin was the first point on the vehicle to hit the dock [4].

The implementation of a shroud around the thruster will alleviate the risk of damage to the propeller. To keep the fins from being damaged, a protective guard could be mounted in front of the stern planes or the fins could be made from a material that would absorb some of the energy of the impact.

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