AFFORDABLE DEEP OCEAN EXPLORATION WITH A HOVERING AUTONOMOUS UNDERWATER VEHICLE

Odyssey IV: a 6000 meter rated, cruising and hovering AUV

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Abstract: The Autonomous Underwater Vehicle Laboratory (AUV Lab) at The Massachusetts Institute of Technology (MIT) is currently building and testing a new, general purpose and inexpensive 6000 meter capable Hovering Autonomous Underwater Vehicle (HAUV), the 'ODYSSEY IV class'. The vehicle is intended for rapid deployments, potentially with minimal navigation, thus supporting episodic dives for exploratory missions. For that, the vehicle is capable of fast dive times, short survey on bottom and simple navigation. This vehicle has both high speed cruising and zero speed hovering capabilities, enabling it to perform both broad area search missions and high resolution inspection missions with the same platform.

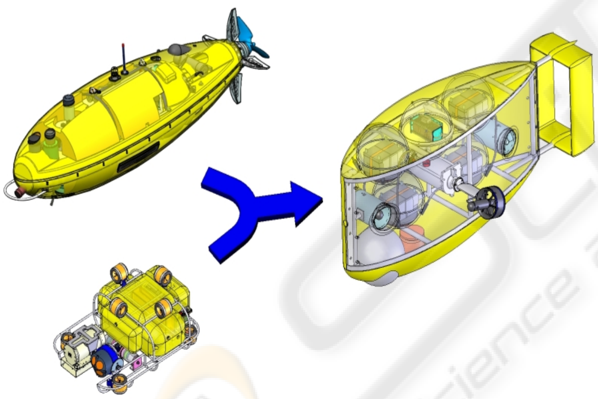

Figure 1: Design evolution towards an underwater vehicle capable of both high speed cruising and zero speed hovering. *Top left* Odyssey II, *bottom left* ONR HAUV, *right* Odyssey IV

1 INTRODUCTION

1.1 Motivation

There is a lack of deep submergence vehicles available to the ocean science community (National Research Council of the National Academies). The valuable resources that do exist, such as the manned submersible Alvin, are under such heavy demand that the scientists who compete to use the resources are severely limited in the types of exploratory missions they are able to pursue. The competition for these assets limits scientists to working in areas where there already exists enough knowledge from previous missions that they are nearly guaranteed to return with a good data product. As a result it is difficult to secure funding to investigate new and completely unexplored areas of the ocean. The Odyssey IV class autonomous underwater vehicle has been designed to perform quick and inexpensive exploratory missions in areas where little or no prior knowledge exists.

This vehicle is intended to be an inexpensive asset that will be readily available for the deep ocean science community, and can be replicated easily. It is not meant to serve as a replacement for the human occupied vehicles such as *Alvin, Mir* and *Nautilus* submersibles, but rather can be used as an inexpensive means of performing preliminary surveys of areas that will potentially be explored by the larger, more capable assets. The data product from this platform will be substantially reduced compared to the more expensive assets, however the lower operating costs will enable this vehicle to

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perform exploratory missions that would not be possible otherwise. Ultimately, it is our intent that this vehicle will provide scientists with a less expensive and more available means of investigating new and unexplored areas in the deep ocean, e.g., those with cold corals (Rogers, 2004).

1.2 Concept of Operations

In order to perform these quick exploratory missions in a wide variety of sites, it is essential that this platform be highly mobile so that multiple sites can be investigated in a single day. Traditionally deep diving vehicles such as Alvin and ABE use external long baseline (LBL) acoustic networks for navigation. The LBL systems are very time consuming to deploy, survey in, and recover. The ship time dedicated to the LBL system forces scientists to dedicate at least several days to any site of interest. The Odyssey IV class AUV is designed to operate independently of these LBL networks in order to investigate several different sites in a single day. The Odyssey IV will be tracked with a ship-borne ultra-short baseline (USBL) system and navigation updates will be periodically sent via the acoustic modem.

To further reduce the ship time required to investigate any given site, the Odyssey IV is designed to rapidly dive to depths as great as 6000 meters using a large external drop weight. This descent weight and the highly streamlined body enable the Odyssey IV to achieve vertical descent speeds as high as 3.5 m/s, compared to the maximum descent speed of 0.5 m/s for Alvin. The round trip travel time to descend to a depth of 3000 meters would require approximately 30 minutes for the Odyssey IV or at least 3 hours for Alvin. In order to achieve these large descent speeds, it is crucial that the vehicle be passively stable in tow. Simply put, the body should travel smooth and straight when being pulled to the bottom with a large weight, without the use of any actuators. Relying on an active control system to reject any wild oscillatory motions on the descent would place a high requirement on the bandwidth of the control system, and would also waste energy which could otherwise be spent collecting useful data at the bottom. To achieve passive stability in tow, a significant portion of the design effort was focused on the hydrodynamics. The results of our hydrodynamic experiments and simulations will be presented later in this paper.

2 DESIGN

2.1 Lessons from Previous Vehicles

The initial design criteria for this vehicle was based on the knowledge gained from previous experiences in designing, building, and operating AUVs in the field. This vehicle is designed to be manufactured and operated at a low cost. By relaxing the packing efficiency constraints, this design will save time and cost by eliminating the need for highly customized components that are required for extremely compact designs.

ODYSSEY IV Specifications	
Weight	~350 kg
Overall Length	2.6 m
Overall height	1.3 m
Overall width	1.3 m
Thrusters	4 x 1hp Deep Sea Systems
Max Thrust per axis	400N
Surge velocity	3.5m/s
Heave velocity	1.0m/s
Sway velocity	0.5m/s
Yaw velocity (hovering mode)	20 degrees per second
Dive speed (with 10 kg weight)	>200m/min
Reserve buoyancy (for payload)	30kg
Depth rating	6000 meters
Budgeted price (excluding labor)	$170,000
Battery technology	lithium ion
Onboard Energy stored	4500 Wh
Power available	6000 W
Controlled DOF	4 (Surge, Heave, Sway, Yaw)
Righting moment	120Nm at 45 degree pitch
Drop weight	1 external for descent, 1 internal for ascent

The size of the vehicle is driven primarily by the desired payload capacity and the use of commercial off the shelf components. The size of the AUV is limited by the typical deck size and crane capacity for vessels of opportunity (Damus, 2004 - a). The size of the vehicle adds to the cost of shipping, which accounts for a substantial portion of the operating budget.

A good AUV design needs to be very robust to endure the damage that routinely occurs during the launch and recovery process. The frame design needs to be rigid, yet sparse to allow easy access to the housings to perform regular maintenance. The frame and fairing should be made of mostly plastic to minimize the machining costs and corrosion problems.

Good AUV designs are quiet electrically and acoustically, in order to minimize the interference with sensitive payload instruments such as sonars. The AUV should contain enough battery power to support a full day of operation with large payloads.

2.2 Cruising and Hovering

Cruising AUVs are generally torpedo shaped, and are optimized for efficient surveys and long range transit, see Figure 1. Cruising AUVs have very limited maneuverability and therefore lack the ability to make sharp turns, to stop for inspection, or to travel at low speeds to closely follow a rough sea floor. Obstacle avoidance becomes a major problem for high speed cruising vehicles operating near the sea floor (Damus, 2004 - b).

Hovering AUVs are highly maneuverable, which makes them ideally suited for short range, high resolution inspection tasks such as ship hull inspections. Most hovering AUVs are not streamlined, and therefore have low top speeds and limited range. The limited range and speed of hovering vehicles makes them ill suited for searching wide areas.

The Odyssey IV was designed for both high speed cruising and zero speed hovering. A highly streamlined and maneuverable vehicle has a much broader range of mission applications. The ability to both cruise and hover makes the Odyssey IV a well adapted platform for wide area searching and for close area inspection, or possibly physical sampling and manipulation tasks in the future.

2.3 Symmetry and Stability

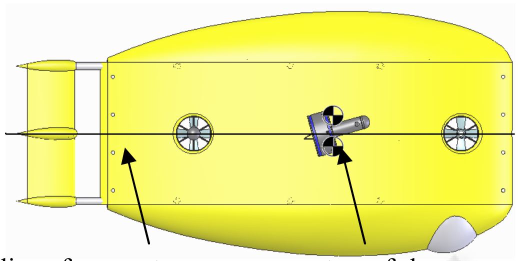

Figure 2: Odyssey IV has highly symmetric thruster placement and a large hydrostatic righting moment

Asymmetries in the body shape and thruster placement cause large torques on the body which significantly increase the bandwidth and power required by the control system. For example, a strong coupling between surge and pitch in the hydrodynamics wastes energy because pitch actuation is required to achieve pure surge. Large disturbances in the dynamics cause navigation errors and discontinuities in the payload data.

Our previous hovering AUV could independently control all six degrees of freedom in the body motion, however the current and foreseeable applications have only required the roll and pitch to be maintained at zero (level flight). The relatively fast dynamics on the rotational axes places high demands on the control bandwidth and authority. Achieving level flight on the roll and pitch axes using passive hydrostatic stability eliminates the need for actuators dedicated to those axes. Reducing the number of actuators has obvious benefits for the overall cost, size, and power budget. A large hydrostatic righting moment causes a high degree of passive stability. A large hydrostatic righting moment is achieved by maximizing the vertical separation between the center of volume and center of mass, which was the major design reason for the elongated vertical shape.

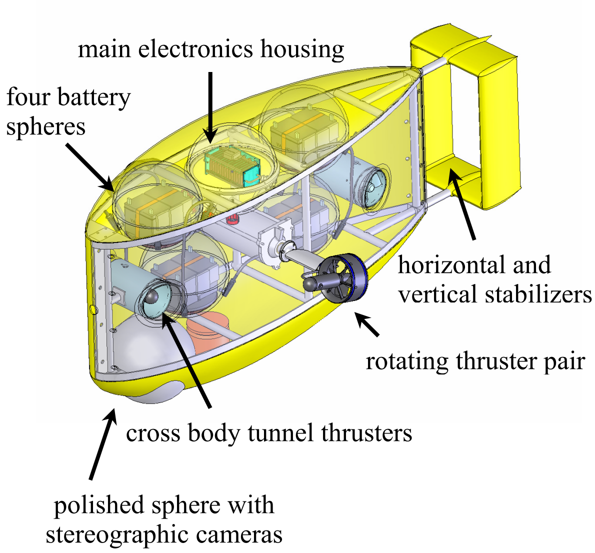

Figure 3: Simplified view illustrating the major components of the Odyssey IV design

Four degree of freedom hovering capability is enabled by passive stability and symmetric thruster placement. Passive roll and pitch stability are enabled by a large hydrostatic righting moment (121Nm at 45 degree) and fixed lifting surfaces. Symmetry in thruster placements reduces required control bandwidth and decreases energy required for station keeping. The rotating thruster unit reduces the total number of thrusters, and therefore enables more payload space and a more streamlined shape. The location of the rotating thruster pair was chosen to minimize the heave pitch coupling in the hydrodynamics. The center of gravity has been brought as close as possible to the line of symmetry in the vertical direction, in order to minimize the cross coupling between the body axes in the hydrodynamics.

3 HYDRODYNAMICS

3.1 Range and Speed

The maximum surge velocity of the Odyssey IV is 3.5 m/s. The Odyssey IV has a range of 100 km at 1.1m/s for a hotel load of 100 Watts. This is an estimation that accounts for the varying efficiency of the thrusters at different thrust values and also for the varying coefficient of drag of the streamlined body as a function of Reynolds number. The coefficient of drag for the streamlined body was experimentally measured to be 0.1 at a Reynolds number of 450,000. The hydrodynamic tests were performed at the MIT Towing Tank facility using a 30% scale model.

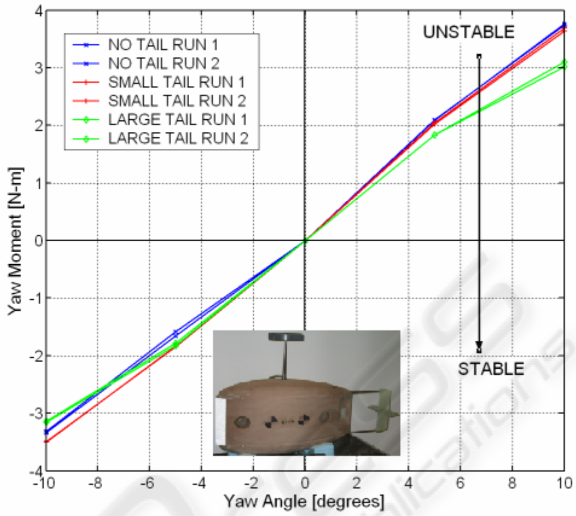

Figure 5: Yaw moment as a function of yaw angle for a series of tail sizes. These results indicate that the tails used for these test have insufficient area to make the body passively stable. In order to achieve passive stability, the rear vertical stabilizer will need to have at least 400% more area. A new model tail is being constructed, and another series of tests will be performed to verify that the increased tail area will enable the body to be passively stable in tow

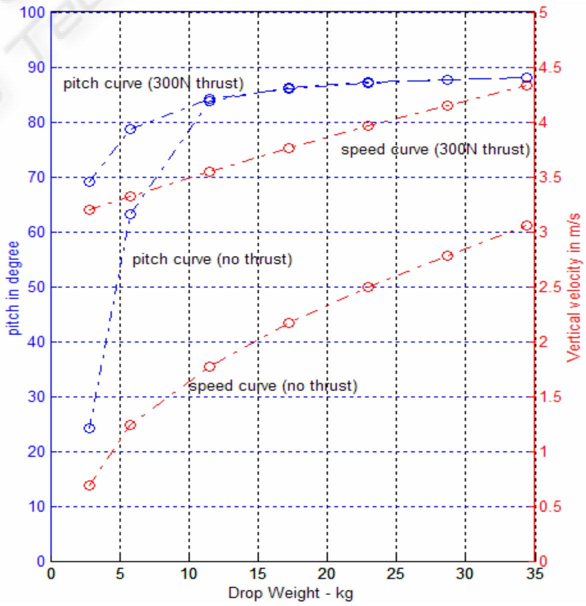

Figure 4: Descent speed and pitch angle as a function of drop weight mass. The weight is placed at the nose to cause the body to pitch down to present a more streamlined axis to the flow. The lift on the rear stabilizers cause the body to pitch further nose down, increasing the speed and stability of the dive.

4 NAVIGATION

ODYSSEY IV has a Doppler Velocity Log (DVL) and an Attitude and Heading Reference System (AHRS) to allow precise dead-reckoned navigation (Whitcomb et al.). During normal cruising, vehicle position will be estimated using an Extended Kalman Filter, with accuracy slowly degrading at a rate of 1-2 percent of distance travelled. However, during deep dives, the DVL will be unable to acquire bottom lock. The high pitch angle of the body will point the transducer head away from the sea floor, and the great depth of the water column will often be beyond the instrument's maximum sensing range. No DVL velocimetry means no position estimates, so the vehicle will have to suspend estimator operation and dive "lost".

Once ODYSSEY IV reaches its target altitude above the sea floor, a subsequent pause to hover in place will enable the science team at the surface to precisely locate the survey start point. The vehicle may be tracked using ship-borne USBL, or GPS-enabled LBL buoys (Desset et al., 2003). ODYSSEY IV is compatible with a fixed LBL net, but we do not foresee frequent use of this mode of navigation, due to the time and expense of deployment. In quick inspection dives, the vehicle need not perform continuous Earth-referenced navigation, but may simply follow a pre-planned dead-reckoned survey path relative to its start point. In post-processing, the estimated vehicle path may be overlaid on a map relative to the georeferenced start point, or the path may be plotted directly from surface tracking data. Experiments are planned to test the feasibility of updating the AUV's self-position estimate with surface tracking data via acoustic modem, such that the on-board estimator can work with Earth-referenced coordinates at all times.

The possibility exists for rapid deployment of multiple vehicles from a single vessel. Each vehicle would be tracked during its dive and its survey start point carefully noted, then each recovered after its mission was completed.

5 PAYLOAD

The Odyssey IV is designed to be a flexible instrument platform, with dedicated space to support a variety of science payloads throughout the lifetime of the vehicle. The high maneuverability, substantial depth rating, low cost and easy deployment of this AUV will make it a good choice for many different scientific inquiries. Odyssey IV has a generous 100 liters of dedicated payload space, and has sufficient reserve buoyancy to carry 30 kg (wet) of additional instrumentation. The main electronics housing has three identical payload ports, each able to deliver up to 2kW peak power from the main battery bus (accounting first for thrust demands). Each payload port can be wired internally for 10/100 Ethernet, RS-232/422/485 serial, and/or general purpose analog and digital I/O, with optically isolated connections to the PC/104-based main vehicle computer.

The first payload planned for Odyssey IV integration is a stereographic digital camera system. A pair of six-megapixel color cameras will share a polished optical viewport in spherical glass pressure housing. The remaining space inside the camera sphere will be occupied by the lighting electronics. These will support one or more strobes (roughly 200 J each), for high-quality still.

Stereo imagery from this camera, displayed through an appropriate stereoscopic device, will enable scientific users to feel as though they are flying over the seafloor along the track of the AUV, with sharp full-color images to examine. After careful calibration of the camera, the raw data may be post-processed into a three-dimensional photomosaic, allowing precise measurements to be made of high-relief targets (typically distorted in 2-D images) (Pizarro et al., 2004).

The other payload sensor that will likely be included in the first generation Odyssey IV is the C3D Sonar Imaging System from Benthos. The C3D system functions both as a sidescan sonar and also as a high resolution bathymetric system. The C3D would be ideally suited for systematically searching relatively wide areas of the sea floor. Targets identified with the C3D sonar could be inspected more closely with the sterographic cameras.

As for more complex instruments, past experience has shown that the 'smart sensor' is a very effective approach to AUV payload development. Despite the additional engineering required, a 'smart sensor' design allows independent construction and testing of the complete subsystem on the bench (and even in limited field deployments) prior to installation in the AUV. The on-board computer is typically responsible for data collection (triggering sensor sampling) and data storage; some devices even perform real-time interpretation (e.g., online CAD/CAC in MCM sidescan sonar applications). Examples of smart sensor subsystems integrated in MIT Sea Grant AUVs include a synthetic aperture sonar (Edwards et al., 2001), mass spectrometer (R. Camilli), high resolution digital still camera and high-frequency sidescan sonar (J. Morash).

Future payloads for Odyssey IV may include solid or water sampling devices. The logical goal of a hovering vehicle is the ability to hold perfectly still - scientists might take advantage of this ability by requesting a returned sample from the seafloor. Simple corers, sediment traps, and biological "slurp guns" have been tested successfully on other vehicles, most notably ROVs (Paull et al., 2001)(Salamy et al., 2001). The high power density available to Odyssey IV payloads may enable more powerful samplers such as chipping hammers for sampling rock or coral.

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